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A State-of-the-Art Review of Equipment Cell Liners for LMFBRs

R. H. Chapman

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REACTOR DIVISION

A STATE-OF-THE-ART REVIEW OF EQUIPMENT CELL LINERS FOR LMFBRs

R. H. Chapman

FEBRUARY 1975

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PREFACE

This review of the state of the art of liquid-metal-cooled fast breeder reactor (LMFBR) equipment cell liner technology was written at the request of the Fast Reactor Safety Branch of the USAEC Division of Reactor Safety Research. It is intended to provide a basis for determining if additional research and development are needed to permit a more definitive evaluation of cell liner design concepts that might be employed in commercial LMFBRs submitted in the future for licensing.

The scope of the study and the time available precluded an extensive literature survey and a thorough assessment of cell liner technology. The report is based on a review of selected literature references, previously published technology assessments, and discussions with knowledgeable individuals. No attempt is made to evaluate and establish validity of design criteria, methodology, failure modes, failure criteria, and performance of cell liners. Similarly, no attempt is made to provide an exhaustive source of references, although a sizable listing is included along with a selected bibliography.

A number of individuals assisted in the preparation of the report. In particular, the contributions of T. W. Pickel and R. A. Just of Oak Ridge National Laboratory; R. K. Brown and associates of Hanford Engineering Development Laboratory (FFTF site); J. M. Dunstan, J. W. Hempe, and H. S. Tsang of Bechtel Corporation (designers of FFTF containment); F. Oplie and associates at General Atomics; and D. W. Goodpasture, structural consultant, University of Tennessee, are greatly appreciated. D. D. Reiff, Fast Reactor Safety Branch, USAEC Division of Reactor Safety Research, and M. H. Fontana, Oak Ridge National Laboratory, provided liaison and programmatic direction for which we are grateful. Thanks are also due to Dolores Eden and Viola Erickson for typing the first draft and to Linda Dockery for typing the final report.

ABSTRACT

Cell liner design concepts and practices used in liquid-metal-cooled fast breeder reactor (LMFBR) systems were surveyed to ascertain the manner by which the functional requirements were satisfied, the severity of sodium spills the liners were designed to accommodate, and the problems encountered in design and construction. The survey was limited to "loop-type" LMFBRs, with primary interest on recently constructed plants.

The report discusses steel-lined concrete structures; describes cell liner designs used in several LMFBR plants, with particular emphasis on the Southwest Experimental Fast Oxide Reactor (SEFOR) and the Fast Flux Test Facility (FFTF); and identifies research and development believed necessary to permit a rational and thorough assessment of cell liner design concepts.

Early reactor plants emphasized the liner as an aid in maintaining an inert-gas atmosphere in the cells during normal operation and as a barrier against leakage of radioactivity under accident conditions. Design criteria included pressures and temperatures expected from sodium reactions with the oxygen in the cell. More recent designs have also considered the liner as a barrier to prevent contact of the hot sodium with the concrete structure. In particular, the designers of SEFOR and FFTF assessed the performance of the cell liners under assumed massive spills of coolant from the primary components and systems; secondary (i.e., nonradioactive sodium) systems and sodium sprays and jets appear to have been excluded from consideration in all plant designs. Guard vessels have generally been provided for protection against spills from components; double-walled piping has been used in some instances.

Practically all LMFBR cell liners have been firmly attached to the backup concrete structure. The notable exception is the "free-floating" liner concept employed in the FFTF. Other than this example, the concepts have changed very little from those used in the first plants constructed. Although analytical techniques and construction details related to liner anchoring have evolved considerably, innovative concepts, designed to circumvent or alleviate the thermal mismatch between the liner and supporting concrete under massive sodium spill conditions, have not appeared in practice. It is concluded that LMFBR cell liner technology has not yet reached the level of maturity evident in containment technology for

water- and gas-cooled reactors, even though the concepts and construction details are largely derived from these sources.

Perhaps the most pressing research need is an experimental program to identify failure modes, to provide design data, to provide experimental data for validation of analytical models, and to provide proof-of-concept evidence under postulated accident conditions.

Also, since the cost of the free-floating concept is far in excess of that of the "fixed" liner and since there is some evidence that the latter can be designed to accommodate massive sodium spills, there is an immediate need for a detailed design study and evaluation of the two concepts. Such a study would reveal problem areas, deficiencies in analytical models and techniques, lack of input design data, failure criteria, etc., and would permit better definition of needed research and development.

Several additional areas that need data and criteria are presented in the report. While these might be considered to have lower priority than the above, they are believed necessary to enhance confidence in the assessment of cell liner designs.

A STATE-OF-THE-ART REVIEW OF EQUIPMENT CELL LINERS FOR LMFBRs

R. H. Chapman

INTRODUCTION AND SUMMARY

Liquid-metal-cooled fast breeder reactor (LMFBR) building structures are usually divided into two or more zones with different atmospheres, one of which is air and the other an inert gas to eliminate (or minimize) chemical reactions with the coolant if leaks should occur. Thus, for practical purposes, there are two containment structures: an inner (primary) inerted containment and an outer (secondary) containment. The secondary containment normally contains an air atmosphere. (Some of the earlier sodium-cooled reactors, e.g., SRE and Hallam, employed confinement buildings for the secondary containment.) This type of conceptual arrangement tends to produce a multiplicity of equipment cells (sometimes referred to as vaults or cavities) with common walls and slabs for the inner containment structure. Large pipe tunnels provide communication between the various cells. The cells and tunnels, as well as the secondary containment (if constructed of concrete), are lined with a thin steel membrane supported by the massive concrete structural and shielding system.

The primary functions of the inner structure lining are to:

1. provide a leak-tight (or low inleakage) containment for the inert-gas atmosphere during normal operation,
2. prevent (or minimize) release of fission products to the secondary containment under accident conditions,
3. prevent contact of the sodium coolant with the concrete structure in the event of accidental sodium spills,
4. facilitate cleanup operations following an accidental sodium spill.

The design concepts and practices of several liquid-metal-cooled reactors were reviewed to ascertain the manner by which the above functional requirements were satisfied, the severity of sodium spills the linings were designed to accommodate, and the problems encountered in design and

construction. Attention was focused primarily on recently constructed plants. The findings of the survey will be used in part to determine if additional research and development are needed to provide a rational basis for evaluating cell liner designs that may be employed in commercial LMFBRs submitted in the future for licensing. This survey is not intended to be a thorough technology assessment; neither is it intended to provide an exhausted listing of references, although a broad representation is included.

Consistent with the "zoned-containment" philosophy discussed above, most sodium-cooled reactors built to date have resulted in complex cellular structures. Reinforced concrete has been favored for this type of construction for many reasons. Flexibility in concrete construction makes it readily adaptable to forming the irregular shapes of walls and floors. Shielding and structural requirements are satisfied concurrently in a relatively easy manner. Concrete construction is not as sensitive to human error as is the manufacture and fabrication of welded, plate-type steel containment structures. Minor discrepancies in placement of reinforcing steel and in construction of formwork have little effect on the load-carrying ability of the completed structure. In fact, a major error or flaw is required in a reinforced concrete structure to initiate a significant failure condition. Concrete (and steel) structures also tend to relieve highly stressed points by insignificant localized yielding or, possibly, by creep.

On the other hand, a considerable disadvantage results from the use of reinforced concrete. The monolithic structure is porous and has a strong tendency for localized cracking due to the inability to sustain local tension stresses. Although this type of crack formation is not considered detrimental to structural integrity, it does reduce the effectiveness of the structure as a containment barrier and makes it necessary to provide an inner steel lining to assure leak-tight construction.

Most of the early LMFBR reactor plant designs emphasized the liner as an aid in maintaining an inert-gas atmosphere in the cells during normal operation and as a barrier against leakage of radioactivity under accident conditions. Design criteria included pressures and temperatures expected from sodium reactions with the oxygen content of the cell. More recently, LMFBR designs have expanded the functional requirements to include the liner

as a barrier to prevent hot sodium from coming into contact with the concrete structure. In particular, the designers of SEFOR and the FFTF assessed the performance of the cell liners for postulated massive spills of coolant from the primary components and systems; secondary (i.e., nonradioactive sodium) systems appear to have been excluded from consideration in all the plants reviewed. Guard vessels have generally been provided for protection against spills from components; double-walled piping has been used in some instances. Sodium sprays and jets have not been postulated in assessing the performance of cell liners under accident conditions. Experimental work in direct support of design or as proof of concept has not been conducted for liners designed to accommodate massive sodium spills. Some relevant sodium spill experiments have been performed in support of the FFTF fire protection system.

Practically all LMFBR cell liners have been firmly attached to the backup concrete structure at discrete points, much the same as the practice in water- and gas-cooled reactor technology. The notable exception is the "free-floating" liner concept employed in certain areas of the FFTF. Other than this example, the concepts have changed very little from those used in the first plants constructed. Although analytical techniques and construction details related to liner anchoring have evolved considerably, innovative concepts, designed to circumvent or alleviate the thermal mismatch between the liner and supporting concrete under massive sodium spill conditions, have not appeared in practice. It is concluded that LMFBR cell liner technology has not yet reached the level of maturity evident in containment technology for water- and gas-cooled reactors, even though the concepts and construction details are largely derived from these sources.

For obvious reasons, it has been necessary to rely on analysis to infer leak-tightness of cell liners under postulated sodium spill accidents, and it is expected that this practice will continue. This places a heavy responsibility on the designer to specify credible design criteria, to analyze the design with reliable models of demonstrated validity, and to assess the possible failure modes by comparison with generalized theoretically and/or experimentally established failure criteria. When viewed as a whole, the evidence supporting the contention that these actions are satisfactorily accounted for in the current state of the art is not totally

convincing. It is believed that confidence in liner performance can be materially increased if research and development in the areas suggested in the report are pursued aggressively.

Although the behavior of the thin steel liner is intimately related to that of the concrete structure, stress analysis of a liner is usually considered as a separate problem. This derives from practical considerations involving treatment of anchor shearing and liner buckling in the concrete structural analysis. However, since the liner influence on the concrete structure is negligible, separate analyses are considered realistic. In this "uncoupled" approach, the first step is to determine the liner "design" strains from an analysis of the concrete structure under the various design loadings. Since the relatively flexible steel liner is assumed constrained to follow the concrete under all conditions, these design strains are imposed on the liner. A number of stress analysis methods have been developed (and are discussed briefly in the report) for analyzing liners under these loading conditions. In the event of a massive high-temperature sodium spill, gross distortion of the liner is probable, and it is not clear that the liner will be constrained to follow the backup concrete.

Most of the analytical models rely to some extent on experimental studies to either establish empirical design correlations or provide proof-of-concept evidence. Although most experimental data are considered proprietary and thus are not available in the public demain, there are some published results. Some of these are discussed in the report. The approach generally taken has been to conduct sufficient tests and analyses to justify particular design parameters and loading conditions. Only small variations in these experimentally based parameters are permitted; otherwise, additional tests and analyses are considered necessary. This is consistent with the observation of Townley[1] that design of complex structures for high-temperature service has been largely dictated by experience and by the knowledge that certain components gave satisfactory service. He notes, further, that such experience, by its nature, cannot be extrapolated with certainty to structures differing in size, shape, and materials or to different loading conditions.

Structural analyses of cell liners present difficulties, with the greatest of these being related to regions of discontinuities, e.g., penetrations

and wall-to-wall, wall-to-floor, and wall-to-wall-to-floor junctions. Yet it is in these locations that the highest stresses will be concentrated and where failure is likely to initiate. Almost invariably, elastic-plastic analyses using two- or three-dimensional models are necessary to evaluate the stresses and strains in these regions. Design of concrete structures for elevated temperatures and large temperature gradients also presents difficulties. In particular, the allowable design values and the degradation of physical properties resulting from short-term exposures at high temperature levels need clarification for use in assessing concrete structural performance under sodium spill conditions.

Specific design criteria for concrete reactor and containment liners have been recently formulated and released for trial use and comment. It is expected that these criteria will be adopted and will become Section III, Division 2, of the ASME Boiler and Pressure Vessel Code. Although these criteria are not limited to a particular type of reactor and do not specifically mention equipment cell liners, they are presumed to be applicable to LMFBR cell liners. Assuming that the FFTF "hot" liners represent the current state of the art, there are a few areas in disagreement with the proposed code. Also, some facets of design are not (or inadequately) covered in the proposed code; in particular, the treatment of, and acceptance criteria for, liner anchors under combined shear-tension loadings (as might be expected if gross distortion of the liner should occur) are not addressed.

Based on the information reviewed for this study, it is concluded that further research and development are needed to permit a valid assessment of LMFBR cell liners under design and postulated accident conditions.

Perhaps the most pressing need is an experimental program to identify failure modes and patterns, to provide design data, to provide experimental data for validation of analytical models, and to provide proof-of-concept evidence under simulated accident conditions. Consideration should be given to cell liner response to sodium sprays and jets and to massive sodium spills with and without chemical reactions. Previous designs have not been based on or substantiated by an experimental test program.

The two most recently constructed LMFBR reactor plants employed radically different cell liner design concents [i.e., "fixed" (SEFOR) vs "free-

floating" (FFTF)], yet both are claimed to accommodate massive sodium spills without loss of containment integrity. Since the installed cost of the floating concept is far in excess of that of the fixed liner concept and since there is some evidence that the latter can be designed to accommodate massive sodium spills, there is an immediate need for a detailed design study and evaluation of the two concepts under the same set of ground rules. Such a study would reveal problem areas, deficiencies in analytical models and techniques, lack of input design data, failure criteria, etc., and would permit better definition of needed research and development. It is suggested also that design studies be initiated to evaluate new concepts to determine their feasibility and/or practicality. Some ideas that may warrant investigation include (1) the use of a zone of high-temperature, insulating concrete (possibly sacrificial) between the liner and the structural concrete; (2) the use of fiber (chopped-wire) reinforced concrete; (3) the use of stud-type anchors designed to fail under sodium spill conditions without rupture of the liner plate; and (4) the PCRV hot liner concept under development in Austria.

In the critical regions of a cell liner (e.g., corners and penetrations), the surfaces of the liner are usually in a biaxial, compressive stress condition, while significant triaxial stress patterns may exist through the thickness of the plate. Since most of the rupture data used to assess failure were obtained from uniaxial tensile specimens, it is often necessary to predict liner rupture data under multiaxial stresses from these data. It would appear that basic research is needed in the area of fracture mechanics and that research is needed to provide rupture data on liner materials under, as a minimum, compressive, biaxial loading conditions.

A somewhat related problem exists for welded construction. Although it is generally assumed that the liner system behaves as if constructed throughout of materials having uniform properties, it is well known that welds introduce regions where the rupture stress and strain may differ significantly from the parent plate material. Since numerous weld joints are required in the construction of a cell liner, it is suggested that the basic rupture data study include an investigation of the effect of welding.

Design of a massive concrete structure to accommodate significant thermal gradients (that might arise during an accident) often dictates the

structural requirements. This being the case, excessive conservatism with regard to design loadings (and failure criteria) can result in costly structures. There appears to be inadequate design data and failure criteria available to the designer to predict the performance of thermally loaded concrete structures with the desired level of assurance. It is suggested that research and development related to thermally loaded, massive concrete structures would be beneficial.

Similarly, it is suggested that research and development be initiated to provide more definitive information on (1) the physical properties of concretes (both structural and shielding types) as a function of temperature, (2) allowable short-term strength of concrete as a function of temperature, (3) the mechanisms and effects of temperature on concrete degradation, and (4) methods for modeling heat transport through heavily reinforced concrete.

Recently, the ACI-ASME Technical Committee on Concrete Pressure Components for Nuclear Service issued for trial use and comment a "Proposed Standard Code for Concrete Reactor Vessels and Containments." This will undoubtedly become, in due time, the standard design and construction reference for nuclear power plants in the United States. The criteria as presently formulated are not altogether compatible with current LMFBR cell liner concepts and practices. An assessment of the proposed criteria with respect to LMFBR cell liner applications is needed to identify areas of conflict, inadequate guidelines, and lack of acceptance criteria.

Although the report is primarily concerned with cell liners, it is perhaps appropriate to indicate the need for research related to sodium reactions and thermal analyses of sodium spills. It is well known that sodium in contact with concrete produces a rather violent exothermic reaction. There appears to be both mass and temperature thresholds below which the reaction is not self-sustaining. Further research appears needed to define the limits and to permit modeling the reaction kinetics so that cell liner design criteria can be more realistically established.

An inert-gas atmosphere is normally maintained in LMFBR primary equipment cells to preclude or minimize sodium fires. Sodium-pool burning is amenable to analysis and is highly dependent on geometry, cell volume, burning surface area, and heat transfer surface area. Sodium-spray fire

analyses are less exact; oxygen level and sodium temperature, particle size, and quantity have a significant effect on the resulting pressure rise.

The SØFIRE-II and CACECØ programs were used in the thermal analysis of the FFTF equipment cells under postulated accident conditions. These are one-dimensional codes and are cumbersome, inefficient (in computer usage), and require large computer memories. It is suggested that these codes be modified and improved (1) to increase computer efficiency, (2) to include slender, two-dimensional cylindrical geometry to permit better modeling of cells, and (3) to include provisions for cell-to-cell transport of gases through interconnecting pipe tunnels and open penetrations.

Consistent with these needs, the report suggests a skeletal outline of how a research program might be logically structured. It is believed that confidence in liner performance can be materially increased if the suggested research is successfully concluded.

STEEL-LINED CONCRETE REACTOR CONTAINMENT STRUCTURES

Background

Steel-lined concrete containment structures are in widespread use in the nuclear power industry. Based on type of construction and functional application, they may be conveniently classified as prestressed concrete reactor vessels (PCRVs) for gas-cooled-reactor systems, prestressed concrete containment vessels (PCCVs), and reinforced concrete containment vessels (RCCVs) primarily for light-water-reactor containment buildings and equipment cells or compartments (usually of RCCV construction) in liquid-metal-cooled reactor systems. The functional requirements of the inner steel liner are basically the same for all these applications; indeed, the design procedures and the construction features are, in principle, the same and were developed first for PCRVs.

There is an abundance of published literature related to the design of these structures, most of which concerns reactor vessels and containment buildings; very little is devoted specifically to the peculiarities of equipment cells for liquid-metal-cooled systems. This is, of course, to be expected since LMFBR containment technology has not yet achieved the degree of maturity of gas- and water-cooled systems.

Oak Ridge National Laboratory has published or sponsored several reports[2–7] relevant to prestressed concrete containment. Bender[2,3] traced the evolution of concrete pressure vessel design, identified the important considerations, and discussed methods then in use for design of these structures. Tan, of Franklin Institute Research Laboratories, published an extensive bibliography[4] and three critical evaluations.[5–7] The bibliography, originally issued in 1966 and updated and reissued in early 1969, probably represents one of the most complete reference sources (most are annotated) available through 1968. Tan's first two critical reviews[5,6] treated prestressed concrete reactor vessels, whereas the third[7] was devoted to containment vessels.

The Bechtel Corporation has published a number of topical reports related to design of concrete containment structures for nuclear power plants, of which two are of particular interest to this survey: One study[8]

is concerned with design of reactor containment structures in general, while the other[9] treats the design of steel linings for water-cooled-reactor containment vessels. The most recent assessment of the behavior and design methods of steel liners for concrete reactor vessels was published by Lee and Gurbuz.[10]

In addition to the foregoing review and evaluation reports, several international conferences have been convened in recent years to review the status of concrete pressure vessel design and to promote interchange of information. The proceedings of these conferences[11–13] provide excellent summaries of the worldwide experience with these hybrid structures.

The foregoing references, while admittedly incomplete, are believed to be representative of the current state of the art. The overwhelming majority of the references are concerned with steel-lined concrete structures for gas- and water-cooled reactor applications. Although little mention is made of equipment cell liners for sodium-cooled reactors, clearly much of the general technology is applicable to these reactors.

It is perhaps instructive to briefly discuss steel-lined concrete pressure vessels for nuclear power plants in general, pointing out some similarities and differences as applied to various reactor concepts.

The French, in their gas-cooled-reactor program, first used a steel-lined prestressed concrete vessel as a primary containment feature in the Marcoule G2 and G3 reactors.[14] These vessels are horizontal cylinders with concave (outward) heads and have an inside diameter of about 46 ft. They were designed to operate with CO_2 coolant at 216 psia, with the blowers and heat exchangers external to the PCRV. The first "integral" PCRVs (heat exchanger and blowers inside the PCRV) were designed and constructed by the British for the Oldbury[15] station. These are vertical cylinders with flat end slabs, having an inside diameter of 77 ft, and were designed to operate with CO_2 coolant at 368 psia. Spherical PCRVs were first used in the Wylfa[16] power station. These vessels are 96 ft in inside diameter and have a minimum concrete wall thickness of 11 ft. They are believed to be the world's largest PCRVs. They are also of the integral concept and operate at 400 psia. Subsequent French, British, and United States PCRVs for gas-cooled reactors are, in general, vertical cylinders based on the integral arrangement.

Thermal considerations impose significant constraints on the design of concrete structures to avoid thermal stress cracking and concrete deterioration. Most PCRVs have been designed to operate below about 180°F to preclude these problems. Thus, the liner in gas-cooled PCRVs serves, in addition to the pressure seal, as a heat collector. Generally, the coolant flow is arranged so that the cooler gas (at or below core inlet temperature) is in contact with the liner; thermal insulation is also provided to minimize heat flow to the liner. Cooling pipes are attached to the back side of the liner or to the anchors to remove heat conducted through the insulation and heat generated by nuclear radiation absorption in the concrete and to control the temperature gradient within the concrete structure. Thus, PCRVs are distinguished by their high design pressure and the use of a thermal barrier system.

As the unit size of light-water reactors increased in the United States nuclear power industry, economic considerations favored the use of steel-lined containment vessels in preference to all-steel vessels; most all new LWRs employs either prestressed and/or reinforced concrete containment vessels (i.e., PCCVs, RCCVs, or a combination of these). The major differences between PCCVs and PCRVs relate to design pressure and heat removal. Whereas PCRVs are designed to operate routinely at several hundred psi pressure, PCCVs are generally designed for less than 100 psi operation under accident conditions. Also, since the ambient temperature within PCCVs normally does not exceed the maximum permitted for the concrete, elaborate liner cooling systems are not necessary.

As the design pressure for the containment structure decreases toward atmospheric, the use of either reinforced concrete containment vessels (RCCVs) or a combination of prestressing and reinforcement becomes economically attractive. As far as the liner is concerned, the major difference between a PCCV and a RCCV is the stress state of the liner. In a PCCV, the initial high compressive strain imposed on the liner by the prestressed concrete structure is such that strain reversals should not occur under any design condition. On the other hand, the initial compressive strain in an RCCV liner is relatively low, and strain reversals are possible under some design loads.

Basically, containment structures are designed to resist internal pressure and various environmental (i.e., missiles, earthquakes, tsumamis, tornadoes, etc.) loadings. These, coupled with the relatively large expansion volume requirements, suggest that the optimum shape will be spherical, cylindrical, conical, or some combination of these. The containment for pressurized-water reactors (PWRs) has become fairly standardized as a vertical cylinder capped with either a hemispherical or a shallow dome and supported on a flat foundation slab, with or without a large sump near the center. Shallow dome covers are generally used for PCCVs, while hemispherical domes are preferred for RCCVs. With a few exceptions, the foundation slab is always of reinforced concrete (i.e., without prestressing). On the other hand, reinforced concrete, reinforced concrete with only axial prestressing of the cylinder, and fully prestressed dome and cylinder are all widely used for the containment superstructure. Concrete containment vessels in the United States employ welded steel liners, varying in thickness from 1/4 to 1/2 in., to effect a pressure seal. The liners are anchored to the concrete support structure by studs, channels, angles, tee sections, or combinations of these.

Since concrete containment has been considered for boiling-water reactor (BWR) applications only recently, vessel configuration is not as uniform as for PWRs.

Steel-lined equipment cells for LMFBRs generally tend to be rectangular parallelepipeds and are related to RCCV construction; at least this is the experience to date. This situation results apparently from equipment layout, economic, and containment considerations. It is a widely accepted design philosophy that rectangular parallelepiped cells are preferable to cylindrical cells, since they provide greater versatility in equipment arrangements for pipeline flexibility, accessibility, and maintenance. Assuming validity of this premise, reinforced concrete construction is probably more economical than prestressed construction in terms of space requirements for the prestressing system and in overall usage of containment volume (primarily cross-sectional area). Although containment integrity may be more difficult to assure with rectangular parallelepiped cells (a

result of the various types of discontinuities present in the construction), this is often not considered to be a serious deficiency since ultimate reliance is placed on the integrity of the reactor containment building.

From the foregoing discussion, it is apparent that LMFBR equipment cell liners constitute a passive protective system, and in this respect they are more closely related to PCCVs and RCCVs than to PCRVs. However, certain cell liner functional requirements are somewhat akin to PCRV requirements. In particular, in the event of a massive sodium spill from the primary circulation system, the cell liner and concrete structural support will be subjected to high temperature levels and may require a heat-removal system to prevent excessive deterioration of the concrete. Also, if severe sodium chemical reactions should occur, moderate to high pressures can be expected. To avoid designing for unusual pressure loadings, an inert atmosphere is usually provided in the cells. Designing for these eventualities implies consideration of certain design features of PCRVs.

Design Considerations

Steel-lined concrete containment structures are rather unique in their adaptability to a wide range of shapes, sizes, and wall thicknesses; in their capability to resist internal and external loads; and in their ability to provide leak-tightness and radiation shielding under normal and accident conditions. They constitute one of several engineered safeguards widely used to enhance the safety of nuclear power plants. Since a high level of confidence is placed in the ability of the containment to function properly when called upon, unusual attention must be given to design, construction, and proof testing of these structurally redundant structures.

Many connotations are implied by design; some of the more obvious ones are sizing of components, formulation of rational methods and techniques for stress analysis, and assessment of failure modes. The mere calculation of stresses and strains does not constitute a design analysis; these must be evaluated in light of failure criteria for the particular materials of construction to provide an estimate of the useful life and the safe margin against failure. Needless to say, the design is not complete until these tasks are performed.

In summarizing structural considerations for fast reactors, Bergstrom et al.[17] pointed out that, while they are not basically different from those encountered in other nuclear power plants, there are some problem areas related to design and construction of the containment. The physical arrangement selected for the inner containment of most sodium-cooled reactors built thus far has resulted in massive, complex structures having a multiplicity of equipment cells with common walls, floors, and ceilings. The nonuniformity in size, shape, and wall thickness makes analysis of these structures difficult. Further, consideration of massive accidental sodium spills leads to additional analytical and construction complications.

As yet there is no mandatory code in effect in the United States covering design and construction of concrete containments. This situation should be rectified in the very near future, since the ACI-ASME Technical Committee on Concrete Pressure Components for Nuclear Service recently issued[18] for trial use and comment a "Proposed Standard Code for Concrete Reactor Vessels and Containments." When adopted officially by ASME, this proposed code will become Section III, Division 2, of the ASME Boiler and Pressure Vessel Code and will undoubtedly become the standard design and construction reference for these hybrid structures. Similarly, a "British Standard Specification for Prestressed Concrete Pressure Vessels for Nuclear Reactors" was also published recently.[19] (This reference was not available for review.) These documents are intended to establish general requirements and acceptance criteria; they do not provide, in general, detailed analytical procedures. It remains the responsibility of the designer to sufficiently analyze the structure using methods based on accepted principles of engineering mechanics appropriate to the geometry under consideration to show compliance with the code requirements and to justify the high degree of confidence placed on the integrity of these structures.

The analysis must consider many different combinations of possible loading conditions. These include, but are not necessarily limited to, dead loads of the structure, equipment loads, temporary construction loads, pressure loads arising from normal and accident conditions, earthquake motions, wind loadings, thermal gradients, etc. Although all the possible loadings would seldom occur simultaneously, specified combinations must be evaluated to determine the most severe design condition. Since the allowable

stress condition for various parts of the structure may vary with the postulated load combination, it is not practicable, in general, to estimate the combination of loading conditions that will result in the maximum stress in any particular member. Selection of the proper design loading criteria for the computation of thermal stresses within the concrete is particularly important, since the ultimate cost of the steel-lined structure can be affected significantly. Detailed analytical studies to define the temperature distributions within the concrete structures are recommended[17] to avoid the costly and overly conservative assumptions often postulated for design purposes.

Although the behavior of the steel liner is intimately related to that of the concrete structure, stress analysis of a liner is usually considered as a separate problem. This derives from practical considerations involving treatment of anchor shearing and liner buckling in the structural concrete analysis. However, since the liner influence on the concrete structure is negligible, separate analyses are considered realistic. In this uncoupled approach, the first step is to determine the liner "design" strains from an analysis of the concrete structure under the different design load conditions. Since the concrete support is a massive rigid structure in comparison to the relatively flexible steel liner, it is assumed that the liner is constrained to follow the concrete under all conditions.

Since this survey is concerned primarily with cell (and vessel) liners, further discussion of the concrete structural system will be minimized. Also, the published literature relevant to concrete design for containment vessels is extensive;[4] numerous surveys, evaluations, status reports, and design approaches are available[2,3,5–8,10–13] for detailed discussion of the various aspects of this topic.

The majority of the published literature on liner design techniques and practices pertain to PCRVs, PCCVs, and/or RCCVs as would be expected. But, as noted by Bergstrom et al.,[17] liner designs for LMFBR equipment cells are not basically different from these more general applications. The significant differences derive from geometrical considerations (PCRVs, etc., are generally cylindrical or spherical, whereas equipment cells are more likely to be complex and irregular in shape) and from the functional requirement to prevent contact between the sodium coolant and the concrete

structure in the event of an accidental sodium spill. Thus, the following discussion, while primarily applicable to PCRVs and PCCVs, is also appropriate to cell liners of LMFBRs. It is understood, of course, that detailed consideration of LMFBR cell liners will require certain modifications and interpretations to the more generally established practices.

Normally, the steel liner is attached to the support structure by welding to embedments located at discrete points in the concrete. The embedments may be either headed or bent studs or standard structural shapes (angles, channels, wide flanges, tee sections, flat bars, etc.) or combinations of these. They are referred to as ties or shear connectors, depending on the nature of their function. Ties are necessary to limit deflection of the liner away from the concrete surface, whereas shear connectors are required to maintain reasonable compatibility between the strains in the adjacent concrete and the in-plane (or membrane) strains in the liner. Forces generated in the liner and shear connectors are due to deformation of the support structure and the restrained differential thermal expansion between the liner and the concrete; these forces are thus strain controlled.

In order to satisfy the functional requirements of the liner, the following basic criteria must be satisfied.[6]

1. The liner must be constructed from a ductile material so that local yielding may be accommodated without developing cracks.

2. It must not be permitted to buckle or deform to an extent that jeopardizes any of the performance criteria.

3. The liner thickness should be such that high-quality welds can be made routinely.

4. The thickness must be adequate to withstand loads applied during construction (usually due to placement of concrete) with minimum reinforcement and/or temporary support.

5. It should be of sufficient thickness to withstand the external design loads resulting from partial evacuation or from applied pressures above atmospheric without requiring extensive stiffening ribs and/or ties to prevent its collapse.

6. The liner should be as thin as possible, consistent with the above requirements, to minimize the loads on corner details and the anchor system.

Strains are induced in the liner by action of the concrete support structure in the following ways:[6]

1. deflections of the liner due to concreting loads and diminution of hydration heat,
2. construction stresses arising from the weight of the partially complete structure,
3. stresses from prestressing, if employed,
4. stresses from pressure loadings,
5. shrinkage and creep of concrete,
6. thermal cycling of the system,
7. differential expansion resulting from temperature differences between the liner and the adjacent concrete,
8. departures of the geometrical shapes and material properties from those assumed in the design calculations.

It is noted that some of the above strains are experienced only once, some are time dependent, some are functions of past history, etc. Thus, it is necessary to investigate the strain behavior in the liner (and the support structure) throughout the projected lifetime.

A number of failure modes are usually considered in the evaluation of liner designs. These include buckling and excessive deflection of the liner, rupture of the liner, shear connector failure, concrete failure in the vicinity of the anchors, high strain—low cycle fatigue, and brittle failure of the liner. These failure modes are discussed below.

Prestressed concrete reactor and containment vessel liners are in biaxial compression under most loading conditions. [Liners in reinforced (without prestressing) concrete vessels may be subjected to tensile forces under certain loading conditions.] For this reason, buckling has been a major consideration in the design of liners. In practice, the liner is subdivided into panels (usually square) as a natural consequence of the anchor system arrangement. It is generally accepted that geometric imperfections exist in the panels as the result of the manufacturing processes. These initial imperfections can cause a panel to deflect locally away from the concrete surface due to liner membrane forces, producing bending in the

panel. This localized behavior has generally been referred to as buckling, although it is not technically a buckling phenomenon in the sense of an instability.[20] A more descriptive and, perhaps, appropriate terminology might be "bulging" or "warpage." It is possible, however, for a "snap-through" buckling phenomenon to occur in curved panels if the ratio of anchor spacing to panel thickness is large.[21]

The buckling behavior of thin shells backed by concrete is quite different from that of shells without backing.[22] Therefore, it is unrealistic to apply the results of studies on such shells to cell liners. Also, the behavior of liners anchored to the concrete structure with discrete (studs) and continuous (embedded structural shapes) ties is different from that of liners without anchors. If the liner is not anchored to the supporting concrete, failure under the biaxial compressive stress field is likely to be of a general instability type wherein a large portion of the liner collapses.

The analytical model usually assumed to determine the magnitude of uniform strain at which general instability occurs consists of a strip of the liner (a ring or a ring segment) supported by a rigid external structure. The model is used to determine the strain required to produce an alternate (buckled) equilibrium position; this strain, called the minimum buckling strain, may be used as a failure criterion. That is, if the strain computed for the combined loading conditions exceeds this value, ties should be provided to anchor the liner to the support structure. Kicher et al.[23] reviewed a number of studies in which this approach was adopted. As an example, the results of Chan and McMinn[21] will be discussed briefly. These authors considered a cylinder of infinite length so that the problem could be reduced to a two-dimensional ring. Additional assumptions included:

1. the radial deformation of the vessel is negligible in comparison to the radius,
2. the material is elastic and obeys Hooke's law throughout the buckling process,
3. all the strains are negligible in comparison with unity,
4. the effect of shear in bending can be neglected,
5. friction between the liner and the concrete can be neglected,

6. the bending equation of a strut with a large deflection and subjected to end moments is applicable,
7. the deflection curve can be approximated by a sine curve.

Based on these assumptions, they derived a dimensionless relationship for the theoretical anchor spacing required in the circumferential direction to prevent buckling. The analysis also provided an estimate of the theoretical strain that could be tolerated without buckling. Since the analysis does not consider the effect of initial imperfections on buckling behavior, the results must be considered as upper-limit criteria. Also, as a result of the assumed infinite length, the analysis does not provide axial spacing information. Tan[6] suggests that satisfactory results can be expected if the axial spacing is equated to the circumferential spacing.

Chan and McMinn[21] conducted experiments to verify their analysis using thin steel strips backed by a rigid circular cavity. The results showed somewhat lower buckling strains than predicted; the lack of agreement was attributed to friction. Sudden or "explosive" buckling was observed a number of times without prior indications of such behavior.

Tests[23,24] conducted at Case Western Reserve University supported the theory of Chan and McMinn. In these tests, thin steel liners were encased in thick concrete shells and strained thermally. Although most of the test models were provided with discrete ties (Nelson studs), it was reported that the results of the unsupported test model did correlate with the analysis of Chan and McMinn.

If the liner is attached to the concrete support structure at regular intervals, the failure mode will not be of the general instability type as discussed above. Instead, one should consider[23,24] circumferential (ring mode), axial (strip mode), and combined (lobar mode) buckling of the individual panels as possible failure modes.

Kicher et al.[23–25] studied stud-anchored liners both theoretically and experimentally. The effects of biaxial loading and anchor flexibility were included.[23] Solutions were obtained for two models, one consisting of a two-dimensional cylindrical shell element (panel) supported by rigid studs and the other a one-dimensional (ring) beam segment (with finite or infinite radius of curvature) representing a panel element supported by elastic studs. The analysis is based on the theory of minimum potential

energy and an assumed displacement state. Buckling is defined in terms of Tsien's lower bound criteria.[26] Rectangular stud spacings for various combinations of biaxial loadings are obtained from the first model, and an estimate of required stud size to support a buckled panel is obtained from the second model. Design charts for specifying liner anchor-stud spacings and sizes were being prepared at the time Ref. 23 was published.

Even though buckling of individual liner panels might occur without rupture, it could cause premature failure of the anchors, which, in itself, might lead to failure of the liner. This could be the case if one panel buckled while the adjacent panels retained their original shape, thus imposing high shear loads on the anchors.

The preceding discussion has been concerned with the general stability of the liner, that is, elastic and plastic buckling phenomena. The designer is perhaps more interested in the forces and displacements imposed on a liner and its anchors under specified loading conditions so that the design adequacy may be assessed. It should be noted that there is a close relationship between liner buckling and shear connector failure, since the former can lead to the latter. The techniques used to investigate the forces and displacements are called "stress analysis methods" by Lee and Gurbuz.[27] They report the primary methods in use as follows:

1. one-dimensional analyses:
   a. Parker's method,[20,28]
   b. Doyle and Chu's method,[29,30]
   c. General Atomic's (GA) method,[31,32]
   d. Bechtel's method,[9]
   e. the iterative force distribution method,[27]
   f. the initial stress method.[33,83]*
2. two-dimensional analyses:
   a. Franklin Institute Research Laboratory's (FIRL) finite-element method.[7]

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*Reference 83 came to our attention during the final stages of the report and is therefore out of numerical order.

Parker's method has been widely used in PCRV design in the United Kingdom, and the GA method has been used for PCRV design in the United States. The methods of Doyle and Chu, Bechtel, and FIRL have been applied to light-water-reactor containment vessel liner designs. The iterative force distribution and the initial stress methods were developed in Lee and Gurbuz's investigation.[10] General Atomic is purported[34] to be considering incorporation of the initial stress method into their design methodology for PCRVs.

All the one-dimensional methods consider an idealized segment of the liner in the meridional or circumferential directions. The analytical model consists of a strip of the liner attached to the concrete with a series of anchors. The two-dimensional method considers a section of the liner together with the anchors and surrounding concrete. The principal differences in the one-dimensional analyses relate to assumed boundary conditions, assumed component behavior, and the methods employed to obtain a solution. Lee and Gurbuz[27] provided an extensive evaluation of the various methods, pointing out the differences, similarities, etc.; the reader is referred to the work[10,27,33] of these investigators for details.[83]

Parker's method[20,28] is probably the most versatile stress analysis method in that it permits direct consideration of local variations in liner thickness, liner yield point, anchor stiffness and spacing, initial inward curvature, liner hot spots, and loss of an anchor. However, a difficulty exists in solving simultaneous equations involving nonlinear coefficients resulting from nonlinear material properties. The method of Doyle and Chu[29,30] is essentially a stiffness reformulation of Parker's approach, with the basic difference being the assumption of uniform initial panel forces. This restricts consideration only to those panels symmetrical about a "weak" panel. Since details of the method used by General Atomic were not available (Ref. 31 was unavailable for this review and Lee and Gurbuz[27] provided no details on the procedure used by GA), we are unable to discuss the basic assumptions. Bechtel[9] employs a relaxation method based on uniform design strains. Variations in liner thickness and yield point can be accommodated directly, but variations in anchor stiffness and spacing cannot be included in the analysis. The effect of assumed initial inward

curvature is included by using experimental characteristics of the "weak" panel. Both the iterative force distribution method[27] and the initial stress method[33] are based on the liner model used by Parker; the primary difference is in the technique used to solve the nonlinear simultaneous equations. Average design strain is an input parameter to both methods, thus permitting consideration of variations in panel design strain as well as the parametric variations amenable to treatment with Parker's method.

It is noted that difficulties can be expected in attempting to employ one-dimensional models to analyze liners in the vicinity of discontinuities such as liner penetrations, component support points, wall-to-wall and floor-to-wall-to-wall intersections in rectangular cells, etc. The stress state and the deformations in these complex situations should be investigated by more powerful techniques, preferably by a finite-element, elastic-plastic analysis as discussed by Tate et al.[35]

The practice in liner design has been to use only shear-slip characteristics of anchors; thus, the actual stress distribution in the anchor has been of little interest. Justification of this approach is based on the use of allowable anchor shear forces derived from experimental results. Clearly, for this approach to be valid, it is essential that the experimental models reflect the actual loading conditions in the prototype structure. Tensile forces can be developed also in the anchors by pressure loadings and by buckling (more correctly, by inelastic bending) of an adjacent panel. The magnitude of these forces will depend on the design strains (biaxial). Little consideration has been given to analysis of combined tensile-shear loadings of liner anchors. Presumably, this is a consequence of designing the liner to preclude buckling, and thus the problem never arises. A massive, high-temperature sodium spill will likely cause gross distortion of the liner, subjecting the anchors to a combination of shear and tensile loadings. These should be investigated, since failure of the welds joining the liner plate to the embedded anchors could propagate through the liner.

Concrete failure in the region between closely spaced cooling tubes may occur in lined vessels having tubes attached (by welding) for control of the concrete temperature and the temperature gradient. Such failures may result from high bearing and/or shear stresses; considerable attention has

been devoted to this aspect in the design of PCRVs. Similarly, liner designs employing structural shapes for shear anchors have considered this problem.[9] Local failure in the concrete adjacent to stud anchors is usually not considered,[10] probably because high stress concentrations at these locations cannot be avoided and adequate relief is obtained by localized crushing. The performance of the liner is assumed to be unaffected by local crushing of the concrete adjacent to the anchors.

High strain-low cyclic fatigue of the liner has received considerable attention in PCRV design, although the number of cycles expected in the life of a vessel is sufficiently small that it is relatively easy to avoid fatigue failure. According to some investigators,[36,37] this type of failure is considered highly unlikely in PCRV designs. This may not be a valid conclusion for cell liners subjected to massive spills of high-temperature sodium, since the temperature levels involved are much higher than those normally expected in PCRV applications.

Liners subjected to significant neutron radiation levels undergo changes in physical properties that may be of importance.[37,38] In particular, increases in the nil ductility temperature (NDT) and the yield strength are parameters often considered in the detailed evaluation of PCCV and RCCV liners. Steels having low NDT values are usually selected for PCRV liner applications in high neutron radiation fields to minimize these effects. According to Lee and Gurbuz,[10] the new British standard[19] requires consideration of the effect of increased yield strength in the design of the liner anchor system.

Testing in Support of Design

Practically all liner design concepts rely to some extent on experimental studies. These studies provide, in general, either empirical liner-anchor design relationships or proof-of-concept evidence. The empirical correlations are used in place of more general, theoretical, component behavior models in the various stress analyses discussed earlier. Such correlations are restricted to a narrow range of applicability and cannot be expected to provide general behavioral characteristics. Similarly,

experimental data derived from proof-of-concept tests are limited to the specific test configuration.

Although most experimental data are considered proprietary and thus not available in the public domain, there are some published results. The most comprehensive test program related to liner segments appears to have been performed by Whessoe, Limited, in England.[28,39,40] The behavior of "strong" (flat) and "weak" (initially deflected) panels under simulated loading conditions was studied. Square panels (about 4 × 4 ft) of the same material and thickness as the prototype liner were attached to a thick steel backup plate (simulating the concrete structure) by study anchors, and in-plane forces were applied to the liner by edge compression. Liner and anchor strains and displacements were recorded, and the data were used[28] to derive empirical relationships for subsequent use in Parker's stress analysis model.[20]

Similar test specimens were used by General Atomic in a test program[41] in support of the Fort St. Vrain reactor. In the GA tests, a concrete section was placed between the test panel and a steel backup plate. The studs were wrapped in styrofoam to preclude bonding with the concrete and to prevent applications of shear loads. The concrete section had a circular void at the center of the panel to simulate voids and to permit external lateral loadings. Biaxial compression was introduced in the test panels by in-plane edge forces. One of the four specimens tested had a weld offset, and another had a cooling tube along the center line. These tests were apparently designed to provide proof-of-concept evidence.

Round, spherically dished liner segments were tested in support of the Wylfa spherical PCRV.[28,39] A 6-ft-diam liner segment was attached with anchors to a backup concrete section, and in-plane edge loads were applied around the periphery of the panel segment with hydraulic jacks. According to Lee and Gurbuz,[10] this series of tests is one of the few in which the composite action of the liner and the backup concrete was studied.

Bechtel[9] tested three 1/4-in.-thick × 6-in.-wide × 15-in.-long rectangular plates under uniaxial compression. The plates were initially deformed 1/8 in. symmetrically about the midpoint of the long dimension. The test configuration consisted in mounting the bent plates vertically, with the bottom end fixed, and applying an in-plane load on the top edge. The

plates were unsupported in the lateral direction. Horizontal deflections at the midpoint (on the edge of the plates) and vertical displacement of the top edge were recorded as a function of applied load. Based on the scope and the atypical test configuration of these simple tests, the utility of the test data for design purposes is not at all clear.

Some important results derived from these tests include:

1. The stress-strain relationship of both flat and initially deflected panels can be approximately characterized as elastic—perfectly plastic.

2. The strain required to initiate buckling in the flat test panels (with anchor spacer to liner thickness ratios ranging between 18 and 38) corresponded to the yield strain.

3. In the spherically dished specimens, the required strain was about 2.5 times greater, indicating the beneficial effect of curvature.

Although not related to specific liner design concepts, tests in support of buckling model studies were conducted by Chan and McMinn[21] and Kicher et al.[23–25] These were discussed briefly in the previous section.

Tests have been performed on liner-anchor systems by a number of investigators to obtain data in support of design analysis. In addition to the previously mentioned tests (most of which employed stud-type anchors), "push-out," or shear, tests have been performed on other types of anchors. In this type of test, the specimen is usually a flat panel with one or more anchors welded to it; the anchors are cast in concrete so that the composite is representative of the prototype. Bonding between the test plate and the concrete backing is prevented to minimize friction forces. Shear loading of the anchor is accomplished by applying in-plane forces to the edge of the test plate. Load-displacement (slip) characteristics are derived from the test results. Various anchor systems (e.g., tees,[42] angles,[9,36] and bars[43]) have been investigated.

Static and fatigue characteristics of stud anchors have also been investigated.[44–46] In these "push-out" tests, studs were welded to the face of wide-flange beam sections and embedded in concrete. (Although these tests were conducted in support of design of composite steel and concrete beams, the flange of the beam section may be considered representative of the liner in a steel-lined concrete structure.) In-plane loads

were applied to either the end of the steel beam[45] or to the edge of the concrete section.[44] In the static tests, failure occurred at the shank of the stud by pulling out a portion of the steel flange face at the base of the stud or by pulling the stud out of the concrete backing. Two different modes of failure were noted in the fatigue tests. Most failures initiated at the reinforcement of the stud weld (probably associated with a notch or stress riser) and penetrated into the flange section, causing a concave depression in the flange. In a few cases, failure propagated through the weld joining the stud to the face of the wide-flange section.

At the time of this writing (mid-1974), an extensive test program was being conducted at the University of Tennessee under the sponsorship of the Tennessee Valley Authority[47] to verify the adequacy of liner anchorage characteristics for use in design of light-water-reactor containment buildings. The scope of this program includes:

1. load-deflection tests of prototype anchor and plates, with various gaps between the plate and concrete;
2. pull-out capacity tests for angles embedded in concrete;
3. tests to determine the shear load capacity of fillet welds (joining the embedded angles to the liner plate) at various angles of applied in-plane loads.

Results of this experimental test program will be published upon completion of the study.

Liner Inspection and Testing

Liners are designed to function as leak-tight membranes and, ideally, are constrained to follow the movements of the concrete structural support system. These requirements dictate that the liner material be thin and possess good ductility and weldability characteristics. Current containment building (vessel) practice is to use 0.25- to 0.50-in.-thick carbon-steel liners. Prestressed concrete reactor vessels tend to use somewhat thicker liners, mostly in the range of 0.50 to 1.0 in.

Since high-quality plate material is specified (and can be easily inspected), problems associated with leakage are usually related to joint design and welding, particularly with on-site and in-situ welding. The

variety of joint designs and the total linear joint lengths involved are such that testing for leaks (and locating them for repair) is a formidable task; nevertheless, it must be done with scrupulous attention to assure a leak-tight membrane. Some designs have incorporated a leak-chase system at the liner plate joints and at liner-penetration joints to facilitate leak testing during construction and at periodic intervals during operation.

The proposed code[18] provides minimum requirements for construction testing and examination of liners, with more extensive examination being required for concrete reactor vessel liners than for containment vessel liners. For example, in concrete reactor vessel liners, 100% radiography is required for all butt-weld joints (no limitation on thickness) and 100% vacuum-box testing, using either a bubble solution or a gas detector technique, for all butt-weld joints in liners thicker than 3/8 in. The radiography requirement implies that the liner be installed prior to placement of the concrete backing. On the other hand, containment vessel liners require only spot radiography of those butt welds accessible to this inspection technique. Magnetic-particle and/or liquid-penetrant techniques may be used in lieu of radiography. In addition to these spot examinations for detection of cracks, defects, flaws, etc., all accessible pressure-retaining liner plate welds must be examined for leak-tightness using the vacuum-box technique. Where vacuum-box examination is impossible, due to lack of accessibility or joint design, 100% magnetic-particle or liquid-penetrant examination is required. Although the proposed code does not discuss cell liners, functionally, they are more nearly characteristic of containment vessel liners; presumably, the code rules for this category may be used as a guide.

The frequency and techniques for testing and the allowable leak rates of liners after the plant has been placed in operation must satisfy the regulatory requirements. Integrated leak rate testing, based on either the absolute or the reference vessel method, is usually performed periodically to provide assurance that containment integrity has not been impaired. Zapp[48] reviewed the state of the art of containment testing; the interested reader is referred to that work for a broad discussion of the subject.

DESCRIPTION OF TYPICAL CELL LINERS IN LIQUID-METAL-COOLED REACTORS

Practically all liquid-metal-cooled reactors built thus far have utilized steel cell liners as protective measures. Some of the more recently constructed ones will be described briefly to indicate the concept and design criteria.

Before describing these facilities, it should be noted that the system physical arrangement is often used to characterize reactors of this type as being of the "pot" design or of the "loop" design.[49] In the pot concept, the primary system components (reactor vessel, pumps, heat exchangers, connecting piping, etc.) are closely connected and submerged in an encompassing vessel filled with low-temperature sodium. In the loop concept, the physical arrangement is spread out, with the primary components usually being located in separate steel-lined cells and not submerged in sodium. A discussion of the advantages and disadvantages of these arrangements is not pertinent to the purposes of this report. Suffice it to say that the consequences of a high-temperature sodium spill in the pot concept are ameliorated by the encompassing volume of low-temperature sodium. On the other hand, a massive spill of high-temperature sodium in the loop concept may present very serious problems. For this reason, this report is limited to consideration of cell liners in loop-type reactor plants. As a matter of interest, LMFBR development in France and in the United Kingdom is based on the pot concept, whereas the loop concept is being pursued in the United States, West Germany, and Japan. Both concepts are under consideration in the Soviet Union.

FFTF Cell Liners

The Fast Flux Test Facility (FFTF) consists of a 400-MW(t) sodium-cooled reactor and associated equipment, systems, and structures. This large system (well along toward completion at the time of this writing) will serve as a prototype for large commercial-sized LMFBRs and presumably represents the current state of the art in most areas of sodium-cooled-reactor technology. For this reason, the FFTF cell liners will be discussed in some detail.

Figure 1 shows the general arrangement; safety design philosophy and a summary of facility design (as of July 1972) are described in Ref. 50. An evaluation of the safety of the reactor (as of late 1972) has been published.[51,52]

As indicated in Fig. 1, the FFTF is housed in a low-leakage steel containment building that is designed to prevent uncontrolled release of airborne radioactivity to the surroundings in the event of an accident. The functional requirements, design, and construction details of the containment building are much the same as those widely used in water-reactor plants. (Since this section is concerned with cell liners, further discussion on the containment building will be omitted.) Inside the containment building, a massive concrete structural and shielding matrix subdivides the space below the operating floor into individual equipment cells as indicated in the figure. Cell geometry is generally rectangular with rounded corners; a notable exception is the cylindrical reactor cavity. Cells containing sodium components and equipment are steel lined and act as an inner containment. Primary sodium equipment cells have an inert-gas atmosphere to minimize sodium fire hazards. The containment building and secondary sodium equipment cells have an air atmosphere.

The steel liners of cells that house primary systems and/or components having sodium inventories sufficient to constitute serious fire and/or radiation hazards are designed to accommodate massive spills of high-temperature sodium without loss of containment integrity. (Note that leakage that might escape these cells is still within the containment building.) In addition, the reactor vessel, the primary circulation pumps, and the intermediate heat exchangers are provided with free-standing guard vessels; connecting piping, valves, and smaller components are not provided with guard vessels. Catch pans are used in some instances, particularly with secondary sodium system components. The containment system is described in detail in the system design description.[53] (Since this document was not readily available for reference, the description presented herein is based primarily on information gained from a visit[34] to the FFTF and is supplemented by Refs. 50 and 51.)

Although liner design requirements differ in detail for each equipment cell, two general liner concepts evolved during design of the containment

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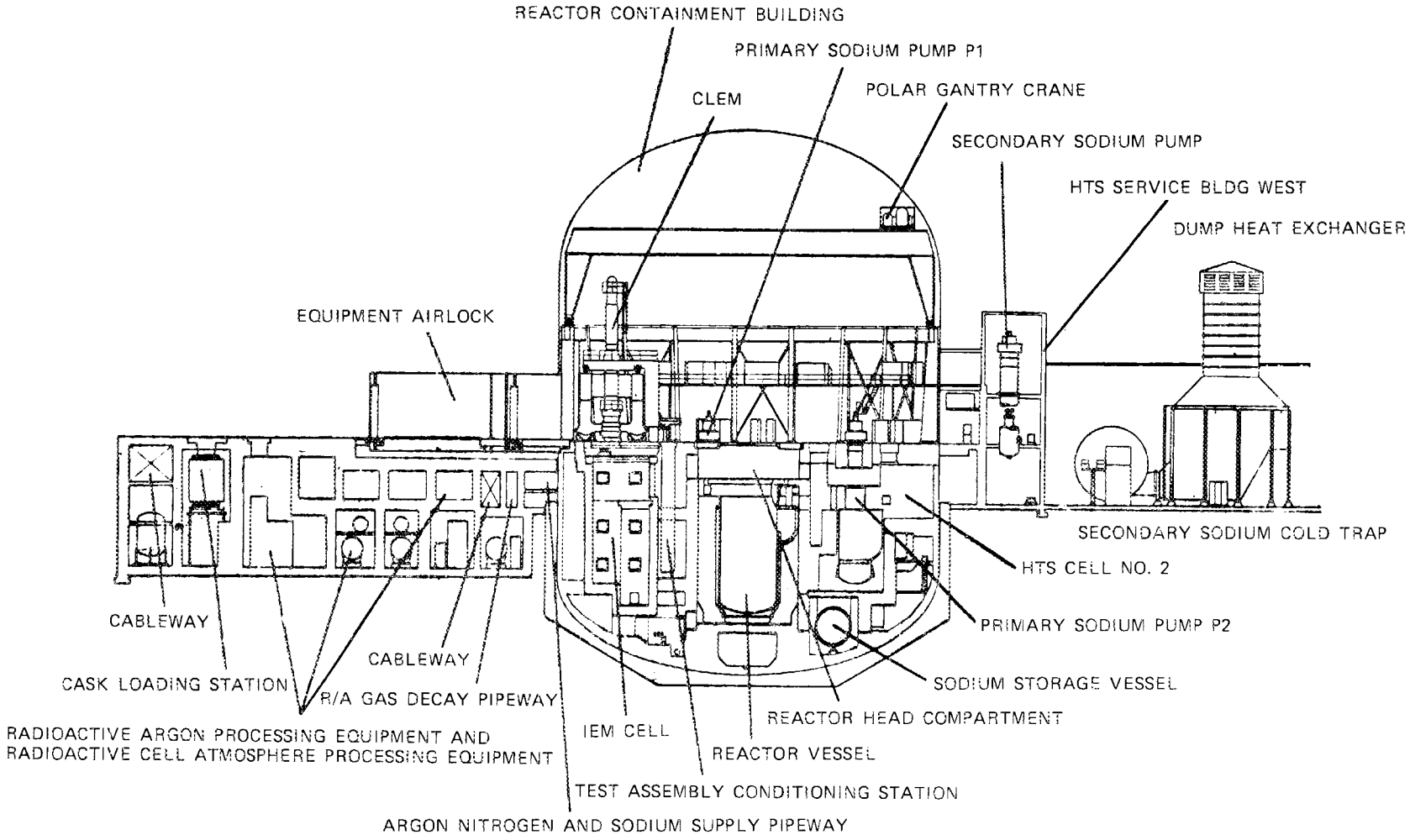

Fig. 1. Fast Flux Test Facility.

system; these are referred to "cold" liners and "hot" liners. Since the hot liner installation is more complex (and expensive) than the cold liner, hot liners are provided only in the lower portion of those cells for which the need was judged necessary, based on the likelihood, severity, and consequences of a primary sodium spill. Cold liners are provided in the upper portion of the hot lined cells and in all other lined cells.

In determining the need for a hot liner and the height to which it should extend, an assessment was made for each equipment cell and passageway of the type and magnitude of equipment failure that might be expected, the temperature and quantity of sodium that would most likely be spilled, and the type and amount of radioactivity that might be released to the cell from the postulated failure. Sodium spills involving sprays and/or jets were not considered; massive spills were assumed to occur from clean double-ended pipe breaks. The quantity of sodium spilled was estimated to range between 7300 (at 1220°F) and 109,000 (at 1050°F) lb, depending on cell, type, and location of the postulated failure. Having ascertained the volume (and depth) and temperature of the sodium pool that might be expected in each cell, a thermal analysis was made to predict the pressure and temperature distribution within the confines of the cell. These predictions were then used as design criteria for analysis of the liner and concrete support under accident conditions.

Cells provided with cold liners throughout are designed for controlled inleakage (1%/day at a cell ambient temperature of 120°F and 1.25 in. H_2O pressure differential relative to the containment building) to the inert atmosphere under normal operating conditions. Since massive sodium spills involving high temperature and/or significant radioactivity levels are not postulated for cells assigned to this category, they are designed for one accident in which the pressure would not exceed 10 psig at 250°F or 12 psig at 150°F without loss of structural integrity. Cells provided with hot liners are designed for the same normal operating conditions as the cold lined cells. However, since massive high-temperature sodium spills are postulated for these cells, more stringent design requirements are specified for accident conditions. For example, the reactor cavity is designed to withstand 35 psig at 150°F for short periods and 12 psig at 250°F for long-term events without loss of containment integrity.

A fine distinction between liner structural integrity and containment integrity appears to have been made by the designers in assessing the adequacy of the design. Apparently, leak-tightness is implied by containment integrity, whereas structural integrity is related to gross failures. For example, if a sodium spill caused the liner to deform significantly and develop small cracks or tears from excessive thermal strains, structural integrity would not be violated (due to the absence of gross failure), but containment integrity might be impaired if leakage occurred.

Actually, two basic cold liner designs are used in the FFTF to provide a rigid leak-tight membrane over the structural (and shielding) concrete support system. One design, quite similar to a concept widely used for water-cooled-reactor containment building liners, consists of 1/4-in.-thick carbon steel (A-516, grade 55) panels welded to 3-in. I-beam sections embedded in the backup concrete on a 4-ft grid. The panels were welded to the embedments, using fillet welds, after the concrete structure was cast and cured. All the corners (floor to wall and wall to wall) are rounded (4 in. radii) to minimize the effect of discontinuities. The second cold liner design concept (adopted during construction) makes use of EFCO modular concrete forms as the basic structural element. These standard steel forms, modified to provide additional supporting angles on a 12-in. grid, were fabricated into large panel sections using groove welds to join the 1/4-in. carbon steel cover plates (the plate thickness was reduced to 3/16 in. for panels assembled late in the construction). The large prefabricated sections were set in place with the smooth side inward (to become the liner) and welded in place to serve as the cell inside concrete formwork. The concrete was then placed to complete the structure. Ultrasonic vibrators were used on the liner side to insure complete filling of the voids behind the liner.

Details of the hot liners differ from cell to cell to account for the particular requirements. The hot liner system is designed, in general, to (1) expand thermally as a result of a hot sodium spill without rupture of the liner, (2) resist the internal pressure generated during an accident, and (3) assure the integrity of the concrete structure by the use of insulating material between the liner and the backup concrete. To maximize free movement of the liner, the plate is anchored only at the top edge, where it joins the cold liner.

Typical hot liner details of a rectangular cell are shown in Fig. 2. The floor liner is carbon steel (A-516, grade 70) with a thickness of 5/8 in. over the major portion of the area. It rests on a 4.5-in. thickness of fire-resistant firebrick (ASTM C-27 heavy-duty type conforming to fire clay refractory requirements of ASTM C-64). A 2.5-in. thickness of insulating firebrick (ASTM C-155, series 20, conforming to requirements of ASTM C-434 for insulating firebrick) is used between the fire-resistant brick and the concrete. The thickness of the floor liner is reduced to 3/8 in. (the same as the wall liner) in the vicinity of the rounded corner sections to increase flexibility. A relief (1-in. depth) in the floor supporting firebrick is provided also in these regions to permit downward movement of the liner. The wall section is supported laterally by fire-resistant and insulating firebrick as indicated. A 2-in. air gap at the bottom of the wall section permits thermal expansion under accident conditions. This relief extends to the top of the firebrick in the corners to reduce restraint in these regions and to provide a passageway for venting. An expansion joint is provided in the wall liners to absorb much of the vertical expansion. The hot liner is anchored only at the top, where it joins the cold liner portion of the cell. Stiffening members are welded over the rounded corners at the bottom of the cell to provide support against external pressure loads during normal operation. (The use of these stiffening members appears to partially counteract the efforts made to reduce restraint in these areas under accident conditions.) Additional details are given in the figure.

Details of the hot liner of the cylindrical reactor cell are shown in Fig. 3. Since the reactor and the guard vessel supporting structure are located at the center of the cell, the floor hot liner is an annular section exterior to the reactor guard vessel support. It is joined to the support by a seal ring to allow for unequal radial movements of the floor liner and guard vessel support due to a temperature differential. A rounded (4-in.-radius) segment joins the floor liner to the cylindrical wall section. The thickness of the floor and wall liner plates is 3/8 in. and that of the seal ring is 1/4 in.; carbon steel (A-516, grade 70) is used as the construction material. The floor portion rests on a 9-in. thickness of fire-resistant firebrick (ASTM C-27 heavy duty conforming to fire clay refractory requirements of ASTM C-64); a 6-in. thickness of fire-resistant firebrick is used

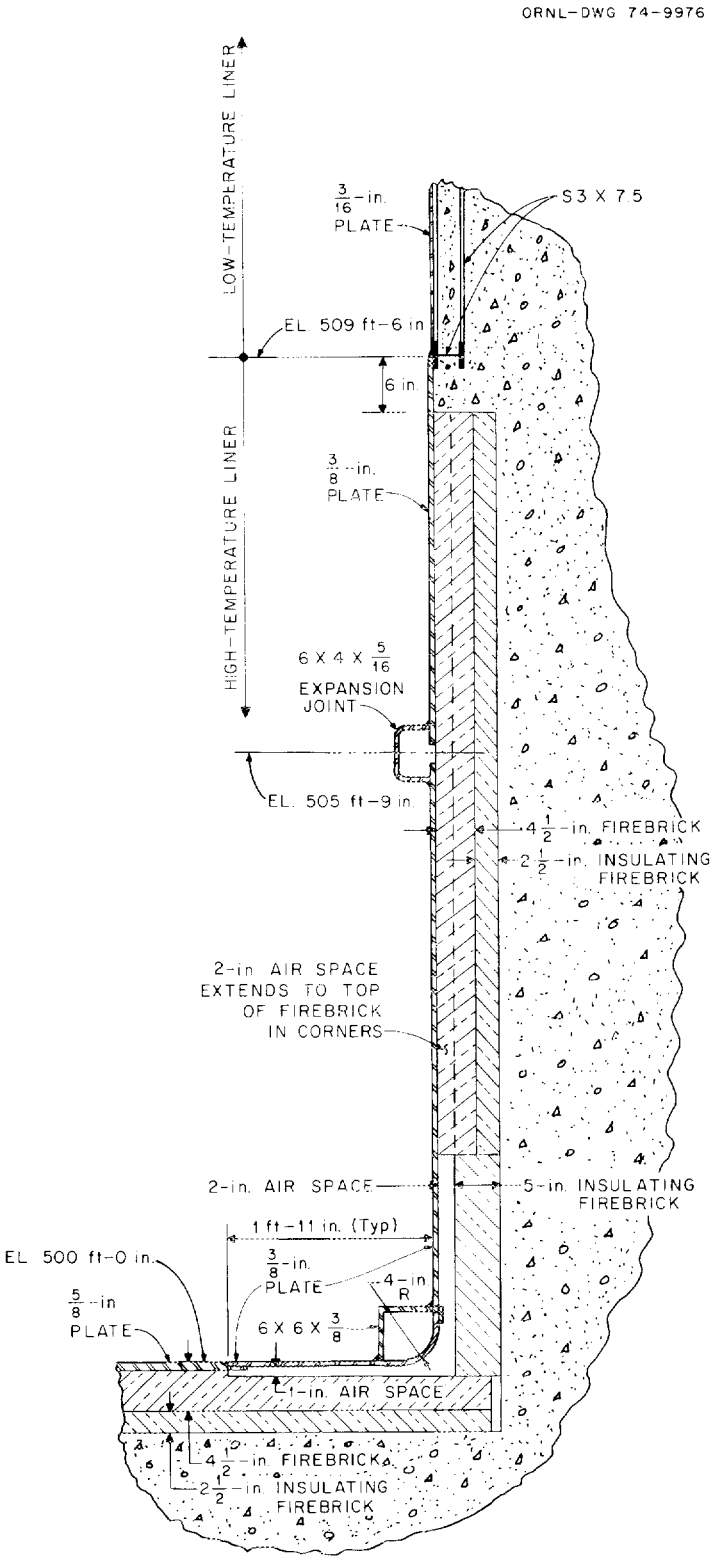

Fig. 2. Typical FFTF hot liner for rectangular cells.

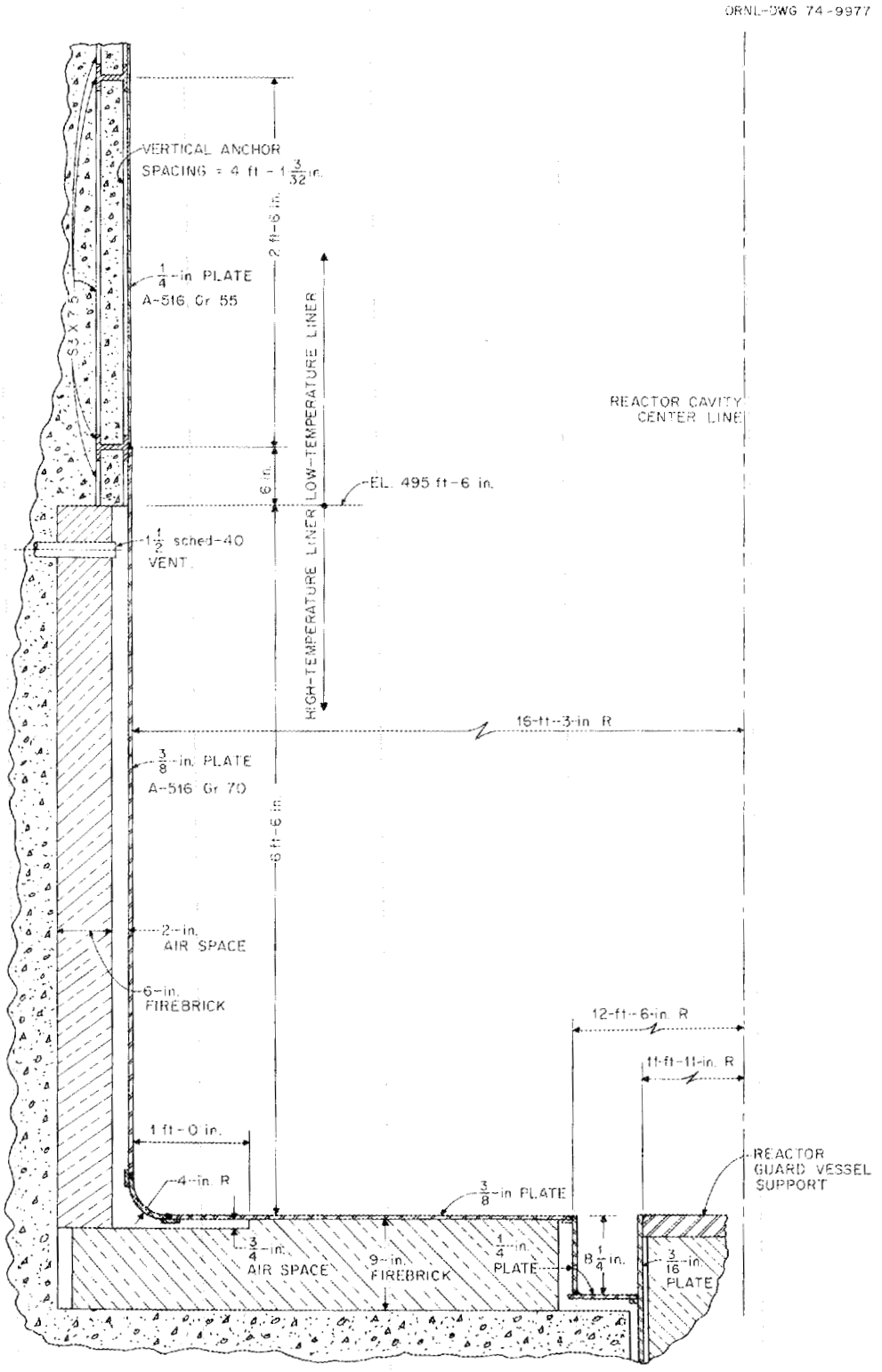

Fig. 3. Details of FFTF reactor cavity hot liner.

in the vertical wall section. A 2-in. air gap is located between the vertical portion of the liner and the firebrick to allow for thermal expansion of the liner with minimum restraint. Similarly, air gaps are provided around the seal ring and at the outside edge of the annular floor. Unlike the other hot lined cells, an expansion joint was omitted in the wall section of this cell liner. (Fabrication of a suitable expansion joint for the cylindrical cavity was cited as the reason for the omission.) Vents are provided behind all the hot liners to allow escape to the containment building of any steam that may be driven off the concrete backup.

Construction of the hot liners proceeded from the outside inward; that is, the concrete was placed first with relief for the firebrick. These were then stacked and mortared in place as required. Large, prefabricated liner sections were then inserted and welded in place using full-penetration butt welds. The liner plate weld joints were visually inspected and leak tested during the erection stage using the vacuum-box soap-bubble technique. Ultrasonic, magnetic-particle, and liquid-penetrant methods of inspection were used to supplement the vacuum-box technique in locations where accessibility was limited. Leak chase provisions are not included in the liner joint designs. When construction of the cell liners is complete, they will be leak tested at design pressure and at ambient temperature, presumably using the integrated leak rate method. Periodic tests during the operating lifetime of the plant must also rely on this method for determining cell liner leak-tightness.

The height of the hot liner required for each cell was determined from a series of thermal analyses, considering the volume and temperature of the sodium spill postulated for that particular cell. The analyses were performed with the following computer programs.

1. SØFIRE-II (a version of the Atomics International SØFIRE program as modified by HEDL) calculates sodium pool oxidation and the accompanying thermal transients and pressure in the gas atmosphere and the enclosing structure by use of a one-dimensional heat transfer model.[54]

2. CACECØ is a sodium fire code[54] that incorporates SØFIRE-II as a subroutine and includes one-dimensional heat transfer into structural walls, floor, ceiling, and other components of the building.

3. HEATING is a generalized three-dimensional heat transfer code[55,56] in which sodium pool and cell atmosphere parameters from CACECØ are used as boundary conditions to calculate more detailed two-dimensional transient temperature distributions in the walls near the pool surface.

The liner temperature was determined as functions of height above the sodium pool and of time. Since structural analyses of the cold liners indicated containment integrity would be maintained (i.e., no leakage) for temperatures up to 205°F (as opposed to the design requirement of structural integrity up to 250°F), the hot liners were extended to the elevation corresponding to the calculated temperature of 205°F. The thermal analysis also provided concrete temperature as functions of distance from the liner interface and of time. The thickness of firebrick was determined to limit the concrete temperature to a maximum of 270°F (originally specified to be 250°F) under accident conditions. Obviously, the thickness of the insulating region is an important design parameter. If the thickness is inadequate, the concrete temperature will tend toward higher values and cause concrete design difficulties and/or uncertain performance. On the other hand, if the thickness is too great, the concrete temperature is favored but the gas temperature will tend to increase and cause higher liner temperatures at a given elevation, making it necessary to extend the hot liner to a higher elevation in order for the temperature not to exceed the design value at the transition to the cold liner. Since the hot liner is considerably more expensive than the cold liner, determination of the insulating thickness has significant economic as well as performance implications.

Stress analysis of the cell hot liners was performed with the MARC-CDC computer program[57] for normal operation, design conditions, and accident (massive sodium spill) conditions. For example, design criteria for the reactor cavity hot liner plate include the following:

1. dead loads, including weights of 3/8-in. liner plate and 1/4-in. seal ring;
2. maximum normal operating negative pressure of 0.15 psig;
3. maximum normal operating temperature of 120°F or a 50°F increment above the erection temperature of 70°F;
4. design negative pressure of 0.25 psig;

5. maximum accident internal pressure of 35 psig in addition to the weight of 4.5-ft sodium pool;
6. maximum accident temperature of 1000°F.

For normal operating conditions, stresses in the liner plate are limited to values equal to or less than the allowable values of 23,200 psi in tension and 24,000 psi for bending. (A room-temperature value of 38,000 psi was used in the analysis for the yield strength of A-516, grade 70 steel.) In addition, the liner should be stable against external load conditions.

For accident conditions, local yielding is permitted; however, calculated strains are specified to remain safely below the expected rupture strain. Based on a typical rupture strain of 0.25 in./in. for structural steels, a conservative value of 0.15 in./in. was assumed for rupture. Allowable strains were taken as one-fourth of this value, or 3.75%. The liner was specified to remain in an elastic state of stress when loaded with the accident pressure shortly after a sodium spill (before the temperature increases appreciably). For this condition, the allowable stress was taken as 90% of the yield stress at 70°F.

A nonlinear finite-element analysis was used to predict the stresses and strains in the liner plate due to the various loads. Input for the two-dimensional model was determined from one-dimensional calculations of force-displacement relations for the cell walls and floors. In most cases, the two-dimensional model was represented by flat, triangular, finite elements. It appears that the three-dimensional stiffness of the rounded segments in the wall-to-wall, wall-to-floor, and wall-to-wall-to-floor intersections was not included in any of the analyses. The wall liner temperature distribution assumed for the stress analysis of the reactor cell is shown in Fig. 4; similar profiles were used for the other cells. (It is not clear from the information available for reference how well the assumed distributions represent those calculated in the sodium spill thermal analyses.) Thermal gradients through the thickness of the liner plate were neglected. This may be important in the very early stages of an accident.

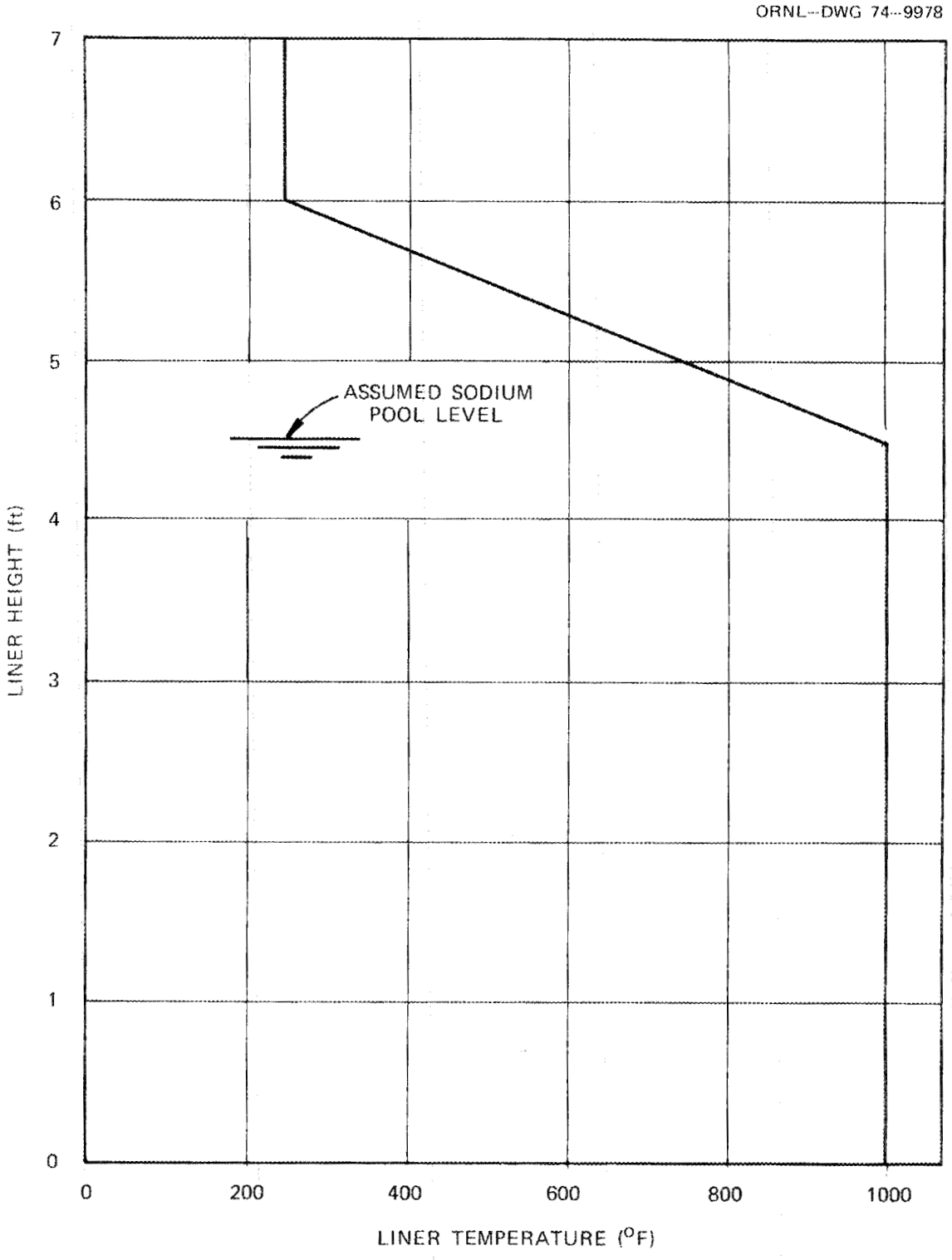

Fig. 4. Temperature distribution used in stress analysis of reactor cavity hot liner.

Nonlinear material properties (at 70°F) used in the analyses are shown in Fig. 5. Temperature-dependent assumptions were as follows:

1. Yield strength is constant at 38,000 psi in the range of 70 to 700°F and then decreases linearly to 26,600 psi at 1000°F.

2. The modulus of elasticity decreases linearly from 29×10^6 psi at 70°F to 24.5×10^6 psi at 1000°F.

3. Poisson's ratio is independent of temperature.

4. The thermal expansion coefficient varies with temperature (in °F) according to $\alpha = (6.1 + 0.0019T) \times 10^{-6}$.

In performing the nonlinear analysis, successive load increments were used; the first increment considered only the pressure loading. For the reactor cell, load increments 2 through 4 considered uniform temperature

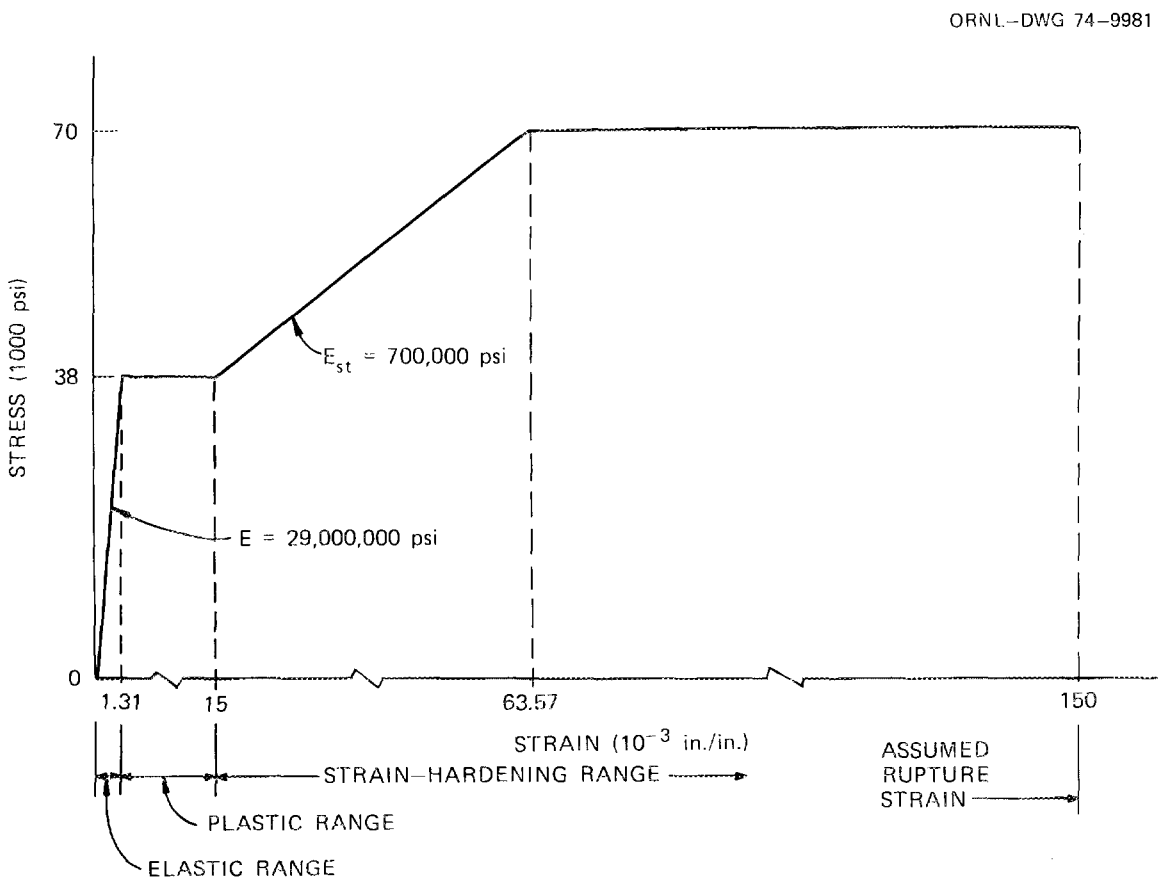

Fig. 5. Nonlinear stress-strain curve used in stress analysis.

increments of 60°F to reach a 250°F uniform temperature; the final 15 load increments consisted of equal temperature increases from the uniform 250°F distribution to the final stage. The final result for this cell shows that yielding occurs at several places, with the maximum strain (8.9×10^{-3} in./in.) at the point where the hot liner joins the cold liner. The computed deflections are shown in Fig. 6. Similar analyses were performed for the other hot liners.

Stress analyses of the cell cold liners were performed using the methods described in detail in Ref. 9 and will not be discussed. As a matter of interest, in the early design stage of the cell liners, attempts to show that the cold liner design concept would also be adequate for massive sodium spills proved unsuccessful. The hot liner concept evolved from these findings and subsequent investigations. Adequacy of this concept is predicated on analysis; experimental testing was not conducted in support of the design. Neither have proof-of-concept tests been performed. Some large-scale sodium spill tests[58–60] were conducted for other purposes and are relevant to the performance of the steel-lined cells. (See also Ref. 84, which came to our attention during the final stages of this report.)

CRBR Cell Liners

The Clinch River Breeder Reactor (CRBR) plant will serve as a demonstration of a commercial-sized LMFBR; design of the facility is in progress at the time of this writing. As yet, detailed consideration has not been given to liner performance criteria and to construction features. It is expected that concepts, features, and construction details found acceptable in the design and operation of the FFTF will be given primary consideration for the CRBR plant. Thus, in the absence of information to the contrary, the concepts previously described for the FFTF are also applicable to the CRBR.

SEFOR Cell Liners

The Southwest Experimental Fast Oxide Reactor (SEFOR) was designed to provide data in support of a test program to demonstrate that fast ceramic-fueled power reactors can be designed with desirable operating and safety

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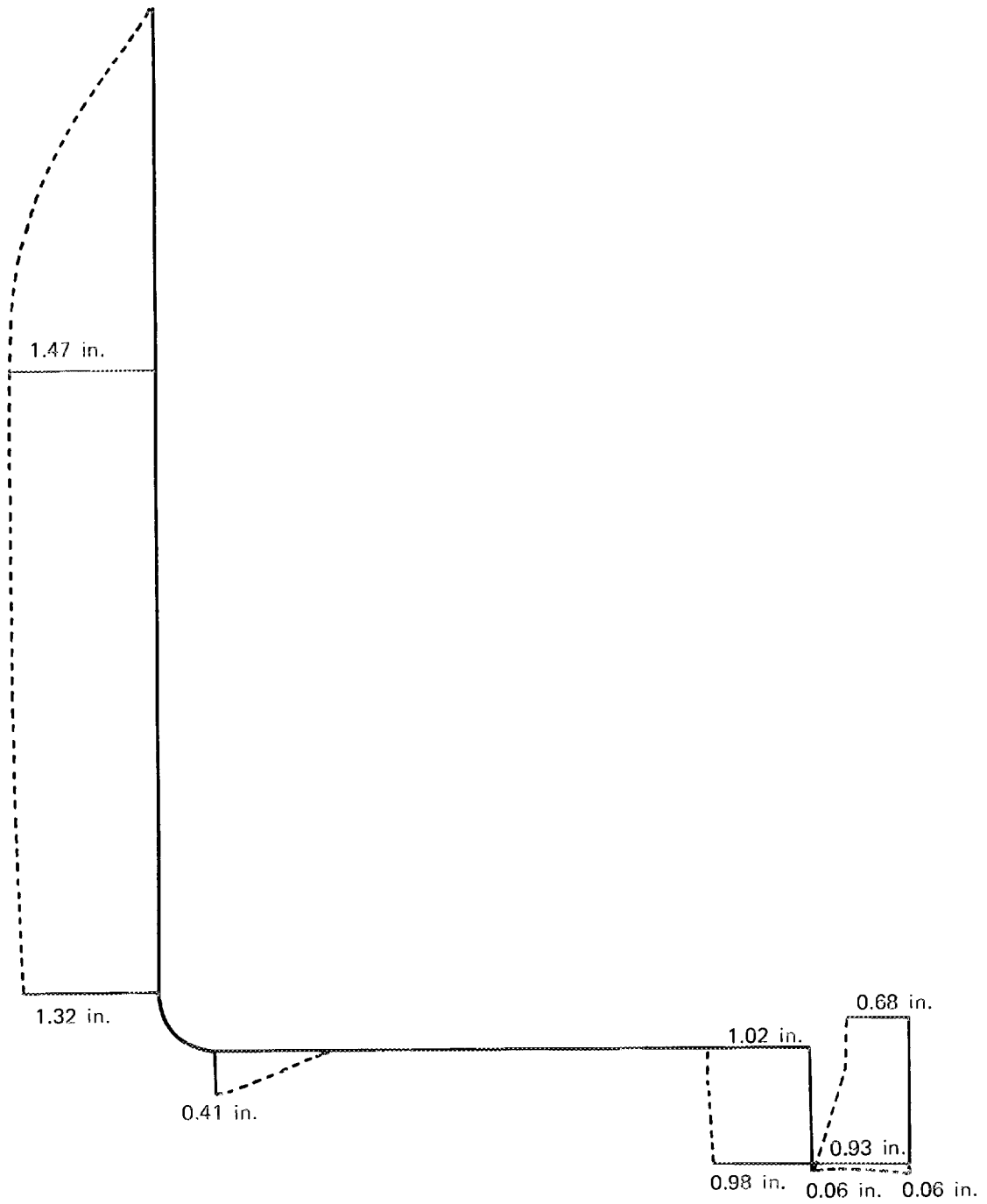

Fig. 6. Calculated deflection of reactor cavity hot liner under sodium spill accident conditions.

characteristics. The 20-MW(t) sodium-cooled reactor is considered representative of the state of the art prior to construction of the FFTF. Construction of the facility was completed in 1968, operation commenced in 1969, and the facility was decommissioned in 1974. Design features and test programs have been reported.[61,62] The discussion given here is based primarily on information presented in Refs. 60 to 65.

The reactor system is housed in a low-leakage steel containment building that is designed to prevent uncontrolled release of airborne radioactivity to the surroundings in the event of an accident. Simplified sectional elevations of the containment building showing the internal arrangement and location of major equipment are given in Fig. 7. The functional requirements, design, and construction features of the steel containment building are much the same as those employed in many water-cooled reactor plants and will not be discussed. As indicated in the figure, a massive reinforced concrete cellular structure provides separation of major systems and/or components; the concrete structure is designed to satisfy structural and biological shielding requirements. Cells housing primary sodium systems are provided with a welded steel liner (shown in the figure by the heavy outline) in intimate contact with, and firmly anchored to, the concrete backup to prevent leakage in either direction and to preserve the inert-gas atmosphere maintained therein as a precaution against fire hazards. The lined cells constitute an inner containment system wholly within the outer (secondary) containment building. Guard vessels are provided for the reactor vessel and other critical components to reduce the probability of losing coolant from regions requiring cooling.

The functional design objectives[63] of the inner containment are to

1. contain the energy and dynamic effects of a design-basis accident of nuclear origin,
2. mitigate the effects of chemical reactions within the containment as the result of the design-basis accident,
3. contain the radioactive material released as the result of the design-basis accident,

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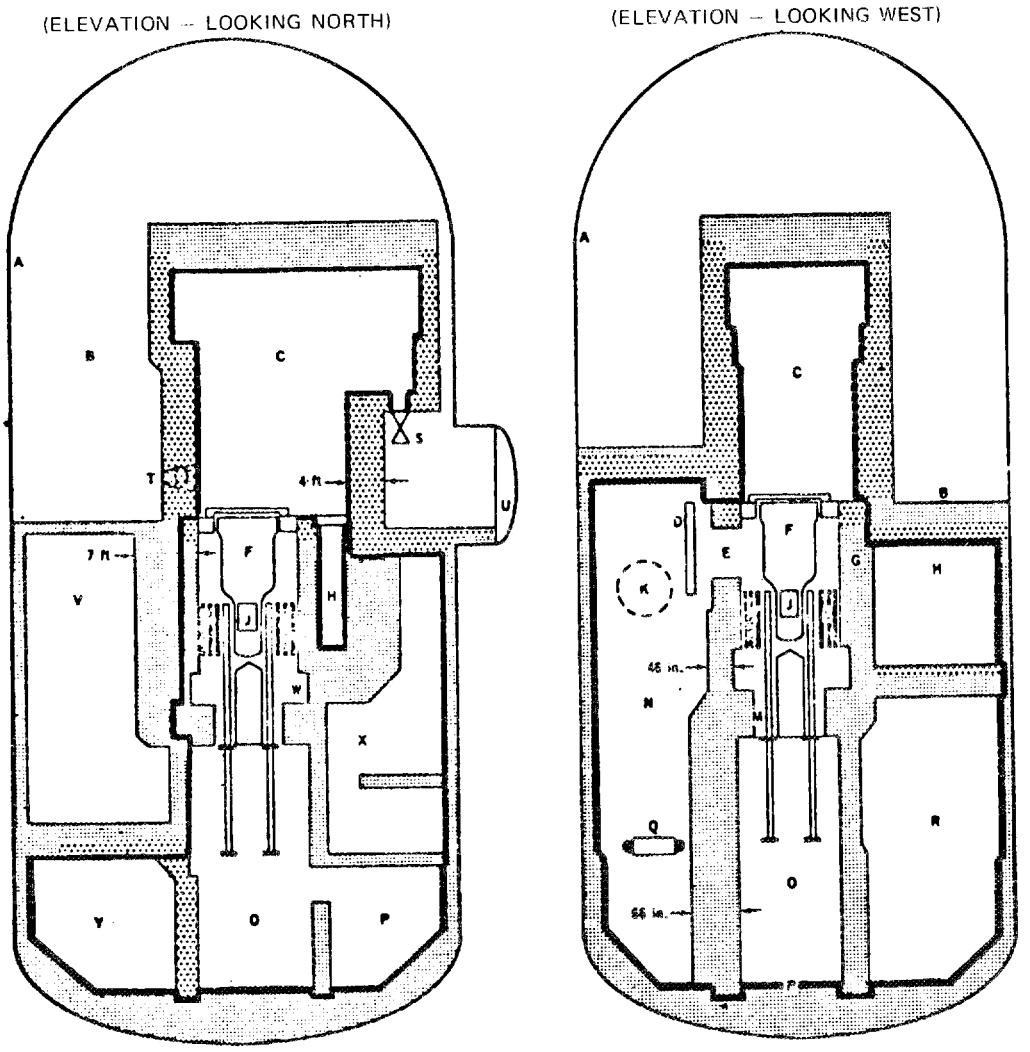

A – CONTAINMENT SHELL
B – OPERATING FLOOR
C – REFUELING CELL
D – SHADOW SHIELD
E – SODIUM–PIPE TUNNEL
F – REACTOR
G – NITROGEN OUTLET DUCTS
H – COLD TRAP CELL AND NITROGEN DUCT AREA
J – CORE
K – MAIN IHX
L – BLAST PROTECTION
M – BOTTOM SHIELD PLUG
N – SODIUM EQUIPMENT CELL
O – REFLECTOR DRIVE CELL
P – STEEL LINER
Q – MAIN PRIMARY PUMP
R – NITROGEN EQUIPMENT CELL
S – FUEL TRANSFER VALVE
T – WINDOW
U – EQUIPMENT DOOR
V – AIR SHAFT
W – N_2 INLET PLENUM
X – NITROGEN EQUIPMENT AREA
Y – SODIUM DRAIN TANK CELL

HEAVY CONCRETE
ORDINARY CONCRETE

Fig. 7. SEFOR reactor building arrangement.

4. suppress and contain chemical reactions and radioactive material that may be released as the result of breaks in the primary coolant pressure boundary.

The inner containment design criteria for normal operation include a pressure loading of 6 in. H_2O maximum (either internally or externally) at a temperature of 200°F. For accident conditions, the design pressure was specified as 10 psig (internal) at 250°F for an unspecified duration of time. All cells were interconnected with rupture disks set to relieve at a differential pressure of 4 psig. The cell liner plates are considered supported continuously by the structural concrete backup without contributing to the support of the concrete. The principal loading considered for the liner plate was derived from an assumed accidental sodium spill (at 1000°F), resulting in a thermal loading causing the panels to buckle between the anchors to relieve the expansion. Leakage was specified to be less than 1% of the contained volume at 10 psig over a 24-hr period.

The massive concrete structure was sized more for its shielding ability than for strength requirements. This resulted in thick, heavily reinforced sections to resist the large thermal gradients existing in the wall sections under accident conditions postulated to last sufficiently long to establish quasi-steady-state conditions. The loadings derived from these thermal moments so completely dominated the design that other types of loadings became relatively insignificant. The method of analysis was outlined by Bergstrom[17] and in the FDSAR.[63,64]

A problem of compatibility of thermal deformations at corners of the concrete cells was not resolved analytically, but it was claimed that the magnitude of the incompatibility was such that very slight plastic deformation of the reinforcement would suffice to allow compatible deformation. In a cell heated from the inside, the concrete panels will tend to take spherical curvature with the convex surface inward. At the juncture of wall and roof, wall, or floor slab, remote from corners (juncture of three slabs), the curvature can be restrained by suitable moment connection in a single direction perpendicular to the edge. As the junction of three slabs at a corner is approached, it is not clear what distribution of restraint moment

and shear is proper. It was assumed that the restraints remote from the corner, if continued to the corner, would be adequate. If the assumption is inadequate, the imperfectly restrained slabs will tend to open at the outside of the corner, consistent with the tendency to spherical bending. The distortion would be limited to compatible thermal deflection and would necessitate only slight yielding of reinforcing near the outside surface to accommodate it. The inside surface would tend to compression, and the liner would be relatively unaffected.

The liner plate, 3/16-in.-thick carbon steel (A-283, grade C), is rigidly attached to the concrete at intervals sufficiently large to allow elastic buckling between the anchors to relieve large deformations. This is claimed to result in an inherently flexible membrane. In addition, the ductility of the plate material provides another mechanism (plastic deformation) for accommodating local strains. Liner plate and anchor details were developed on the basis that the plate would expand and buckle under maximum temperature (sodium spill) conditions.

The design assumed that the maximum positive pressure from the outer containment (6 in. H_2O) penetrated the concrete of the inner containment and would be exerted on the entire outer surface of the steel membrane. This requirement controlled the anchorage to the concrete and the thickness of plate to resist mechanical loading. The other concern for this liner was the thermal loading. For the design operating temperatures and complete restraint of thermal expansion, the stress in the plate would be below its yield strength, although the abutment loads on the concrete at the corners would be slightly higher than desired. For the accident temperature, the stress for complete restraint is above the minimum yield strength of the carbon steel, but much below twice the yield. It was concluded that the accident condition did not pose a serious threat to the liner or the concrete, although the abutment loads would increase. To minimize the abutment loads, liner panels were installed with anchors at 6-ft spacings to reduce these loads by buckling. (Reference 63 gives the 6-ft spacing; Ref. 64 states 1-ft spacing. The information in these references is not sufficiently detailed to clarify this apparent discrepancy.)

Reliance on buckling to relieve loading at the corner junction of slabs did not appear feasible; hence, the loading due to full thermal expansion restraint was assumed at these points. Anchorage to the concrete in the form of embedded strap anchors was provided at the perimeter of the liner panels and at the corners (junction of wall-to-floor slab or wall-to-wall slab) sufficient to resist the external pressure and also to provide lateral restraint against buckling at these support locations. The junctions were formed by angle members anchored to the concrete with the liner plate welded to the angle. At liner plate joints away from the corners, a backing strip was anchored to the concrete by embedded strap anchors, and the plates were welded to each other and to the backing strip continuously as shown in Fig. 8. The anchor bars were proportioned to resist the pressure load, or 2% of the column load for lateral restraint under thermal loading, with normal bond stress. All anchors had bends for additional strength.

In assessing the effect of an undefined massive coolant spill, it was concluded that:

> "A voluminous spill of hot sodium will stress the restrained portions of the liner plate well beyond yield strength, but there appears to be little reason to believe that rupture would occur. In this event, it would appear mandatory to inspect the extent of yielding and re-evaluate the ability of the liner and anchors prior to resuming operation. This severe accident would result in distortion and buckling of the liner, but could not disturb its ability to act as a membrane."[64]

The floor of the refueling cell is 3/16-in.-thick stainless steel (type 304) to resist traffic wear. Since large cutouts for access to the reactor vessel and to the spent-fuel storage tank occupy a large portion of the floor area, relief of thermal expansion by buckling of panels did not appear feasible. Anchorage to the concrete is at intervals sufficiently close to prevent buckling, and initial yielding of the floor and adjacent wall plates would force conformance to the dimensions of the concrete cell. At design operating temperature (200°F) and for complete restraint of thermal expansion, the compressive yield strength will be exceeded. The restraint of thermal expansion will result in plastic strain (that may equal the yield strain) in the unrestrained direction (thickness). According to the designer, the ability to sustain significant elongation indicates that such compressive yielding would cause no distress to the material.

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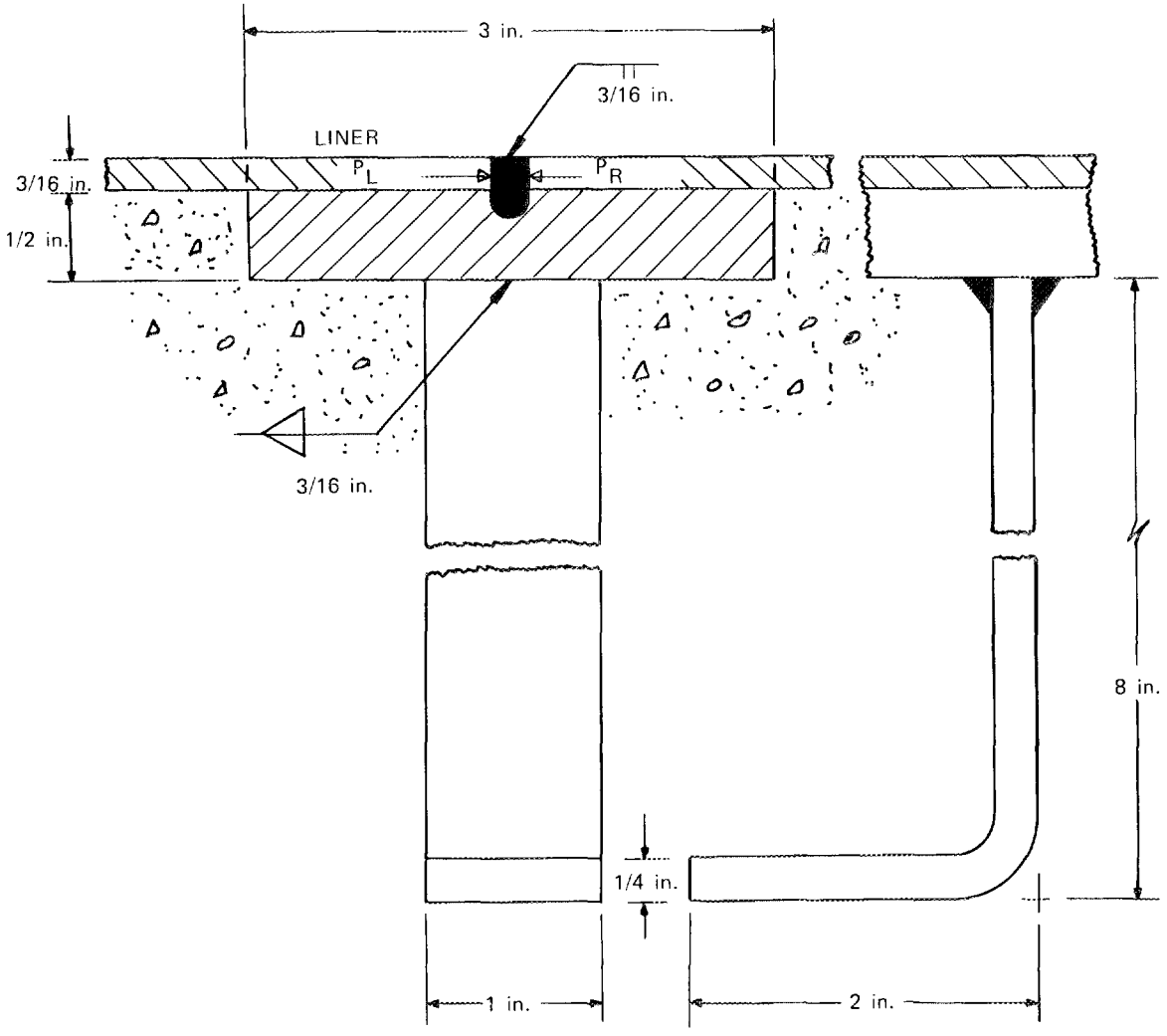

Fig. 8. SEFOR typical liner plate anchor.

The junction of the stainless steel floor and the carbon steel wall liner was not considered to be a serious design problem. A stainless steel angle forms the corner and is butt welded to the stainless steel floor plate and to the carbon steel wall plate. The difference in coefficient of thermal expansion between the wall plate and the stainless steel reduces the restraint stress in the carbon steel from that in the stainless, but the deformations are forced to be compatible by the restraint of the concrete structure. It was concluded that:

> "The design accident temperature of 250°F will result in a plastic strain of about twice yield strain. A hot sodium

spill could result in greater plastic deformation, but a mechanism for catastrophic failure is not apparent. Such an accident would require inspection and review prior to resumption of operation."[64]

The discussion in the preceding paragraphs (and the quotations) is based on information presented on pp. 5–7 of Supplement 7 to the FDSAR;[64] clearly, one would conclude that plastic deformation would be expected in the liner. However, that appears to be contradicted by the answer submitted to Question B-5(b) in Supplement 17 (Ref. 65), part of which is quoted below.

"As stated in FDSAR, Section VII, p 7–8, and discussed in Supplement 7, p 6, the liners are designed so that buckling of the liner plates will relieve the stresses due to thermal expansion well before the yield stress is approached. This is shown in Table B-5.1 which lists the buckling stresses, σ_b, for the A-283-C steel plates in the range of 500–700 psi for a temperature range of 1000°F down to 200°F. The corresponding yield stresses range from 16,000 psi at 1000°F to 39,000 psi at 200°F. Because of the wide margins available, it is concluded that buckling will always occur well before the yield stress is approached."

The effects of variations of +0.017 and −0.010 in. in plate thickness and differences in edge restraint were investigated. It was concluded that these factors affect the buckling stress by only 2 to 3%. Unbalanced anchor forces ($P_R - P_L$ in Fig. 8) resulting from the use of unequal panel sizes in corners and other geometrical irregularities were also investigated. Due to the relatively greater stiffness of the smaller panels, the buckling stresses are greater and lead to unbalanced forces on the anchor. The worst-case combination, consisting of a standard panel (10 ft × 6 ft) joined to the smallest panel (2.5 ft × 1.5 ft), at 1000°F was judged adequate.

The expected performance of the liner can perhaps be summarized by the applicant's response[65] to Question B-5(c) in Supplement 17 of the FDSAR as:

"When buckling is not restrained, the plate deformation would approximate a sine wave so the weld would be loaded in bending. Stresses due to this load would be within the elastic range for the design operation conditions so that cyclic loading would not be a problem. The case of unbalanced loading on the anchor has been covered in the answer to Question B-5b. For the accident case, the stresses would be above the yield strength of the material, but the loading would not be cyclic and the strains

> would be well below the capability of the material. For the sodium spill on the 18" panel (worst case), the strain would be less than 0.6% as compared to the ultimate strain capability of the liner material of about 50%."

and to Question B-5(d):

> "When buckling of the plates or edge members is restrained, the design operating temperature would not cause excessive loading of the plates. The transient temperature rise to operating temperature with the cooling system operating would be a ramp function and not a step temperature change. The coefficient of expansion of concrete and steel are roughly the same and in a gradual rise to temperature, they would expand together. In an accident condition, the sudden rise in containment atmosphere temperature to 250°F could introduce expansion stresses which slightly exceed yield but are much less than twice yield, so that after the first cycle, the steel would remain in the elastic range. In all of these calculations, the initial fit-up has been assumed to be perfect, so that no credit is taken for deformation to relieve stresses; anything less would reduce the stresses. In the event of a sodium spill with plate temperature reaching 1000°F (design maximum temperature), the computed elastic stresses in a restrained member would exceed yield by a large margin, but the data in Table B-5.I indicates that the tensile elongation capability of the metal greatly exceeds the expected compression of the plate. If plastic buckling should occur, the welded juncture would act as a clamped edge, and a sine wave buckling pattern would not load the weld area more severely than the other areas."

The cell liner plates were joined with full-penetration butt welds in accordance with the rules of the ASME Boiler and Pressure Vessel Code. Weld joints that would become inaccessible for inspection during testing of the completed cell were fully radiographed prior to being concealed; joints not amenable to radiography were given a visual inspection. Local leakage checks were performed during the erection stage using a vacuum-box and soap-bubble solution. Leak chase provisions were not included as such, but a network of drainage canals was provided between the liners and the backup concrete; the canals terminated in a sump and could be used in conjunction with leak testing. Upon completion of construction, the cells were pneumatically pressurized to 10 psig (the design pressure) and leak tested using the integrated leak rate test method[48] with a reference volume. After commissioning of the plant, annual integrated leak rate tests were specified to maintain confidence in the containment integrity of the cell liner.

Fermi-1 Cell Liners

The Enrico Fermi power plant[66–68] is a 200-MW(t), sodium-cooled, fast breeder reactor system built in the late 1950's as a commercial demonstration plant. The reactor, fuel handling mechanism, intermediate heat exchangers, primary circulation pumps, and storage tanks are housed in a steel containment building as indicated in Fig. 9. The primary sodium system is located in a concrete structure below the operating floor as shown in the figure. A cross-sectional plan view of the arrangement is shown in Fig. 10. The exposed concrete structure is lined with steel plates as

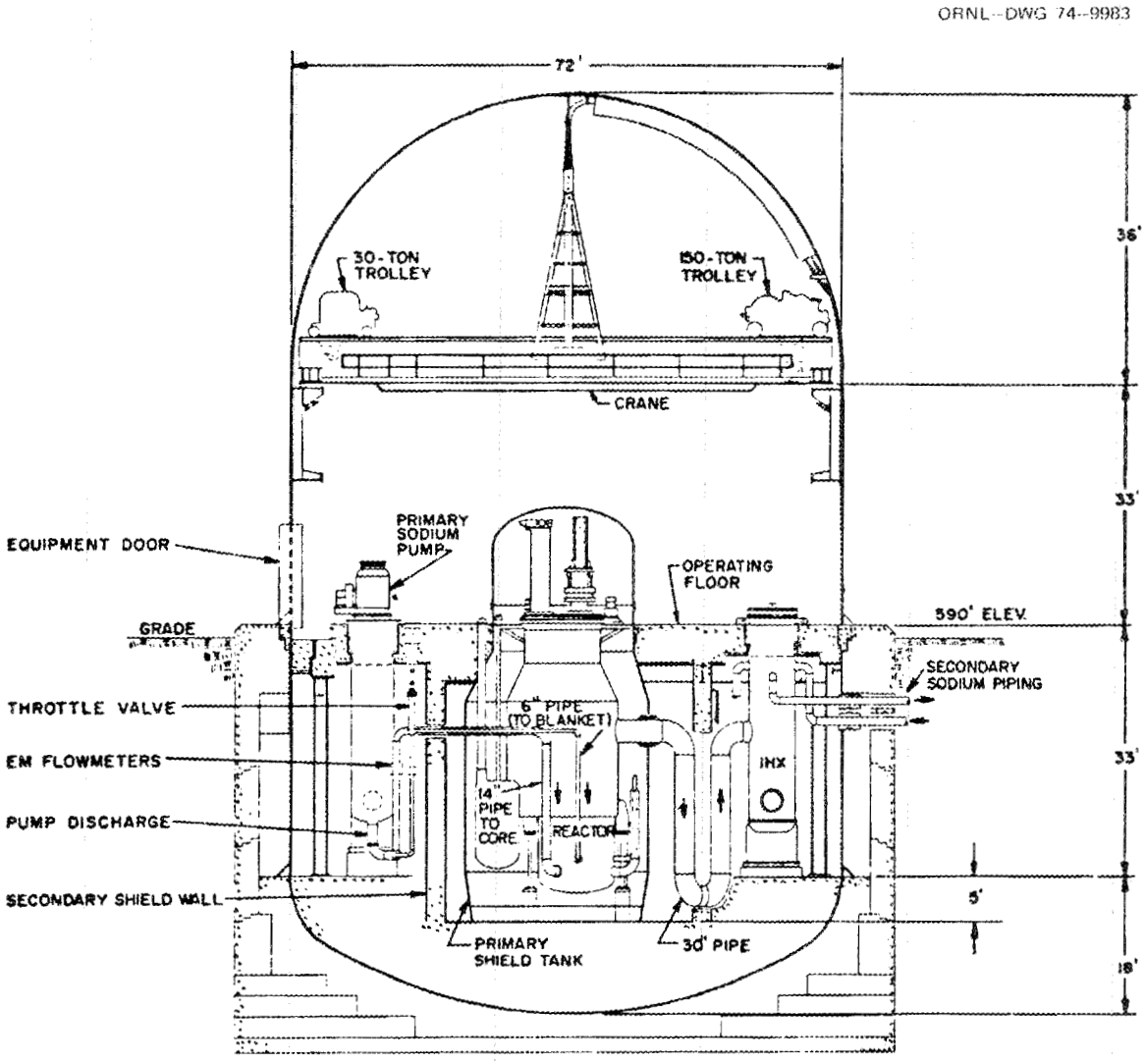

Fig. 9. Fermi reactor building arrangement.

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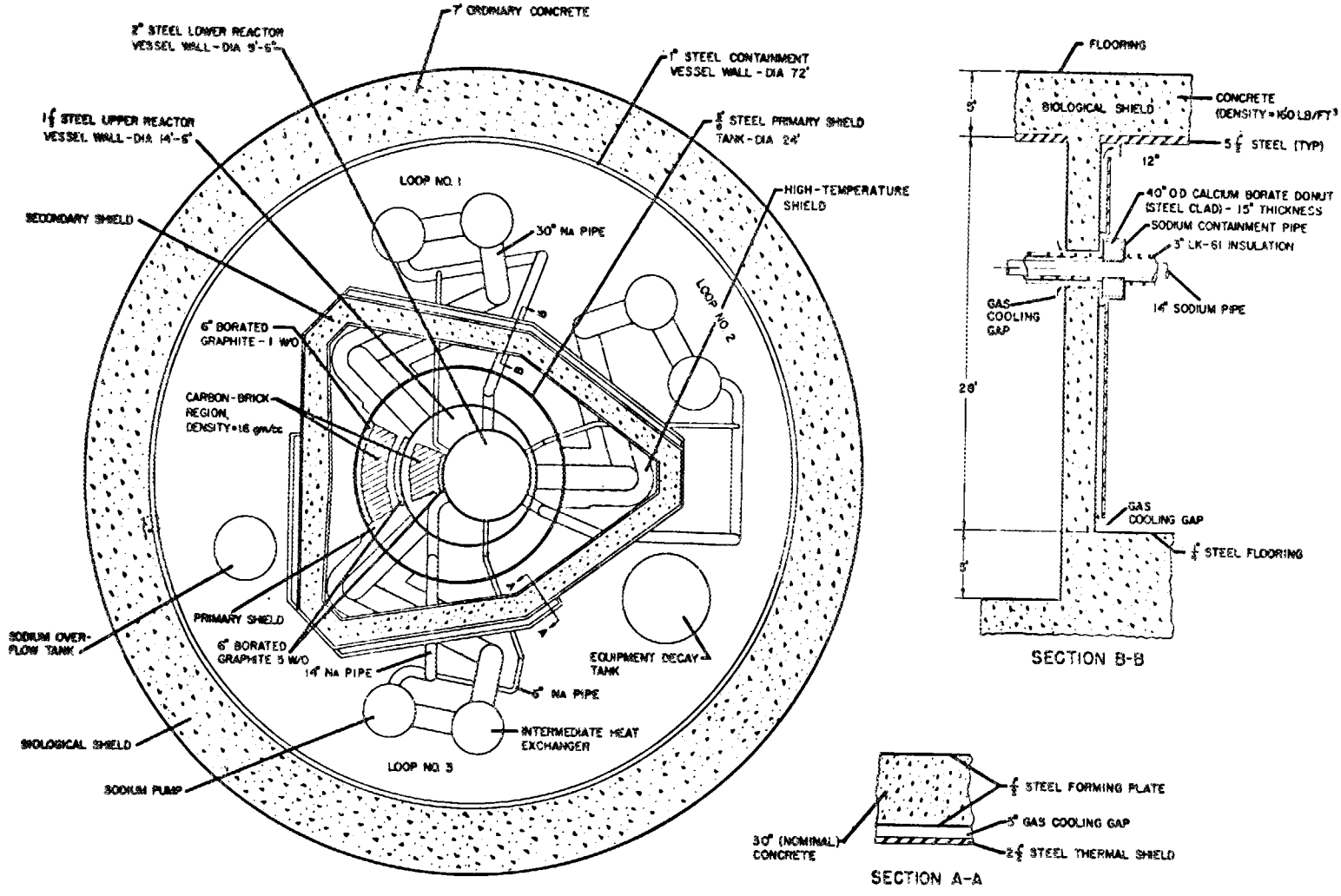

Fig. 10. Plan view of Fermi reactor building.

indicated in sections A-A and B-B of the figure to permit separation of the space above and below the operating floor. (Further details on the liner were not included in the report.[66]) An inert atmosphere is maintained in the sodium equipment spaces as a precautionary measure against sodium fires, and double containment of the equipment is provided to prevent sodium leakage.

The containment vessel was designed according to the rules of the ASME Boiler and Pressure Vessel Code for 32 psig at 650°F. Studies made subsequent to construction of the building showed that the maximum values of 28 psig for the pressure, 460°F for the steel temperature, and 1240°F for the gas temperature were more appropriate values for the hypothetical conditions assumed for design purposes.

In assessing the safety of the reactor, consideration appears not to have been given to a massive sodium spill and its effect on the containment integrity. Primary concern was devoted to release of radioactivity from the building. This is evident from the following appraisal by Amorosi and Yevick:[68]

> "It is difficult to hypothesize an accident as large as the one for which the building is designed. Any credible accident will be contained below the reactor operating floor and, since the air below floor is depleted in oxygen, there is not basis for the assumption that the oxygen in the building will burn at the rate indicated. Nevertheless, the following conditions for the assumed accident were considered. On a windless day in summer with the air temperature 100°F and the building metal temperature 125°F, a major sodium leak develops below the operating floor, and the reactor, which has been operating at 430 MW to a maximum of 6% burn-up, loses most of its coolant. Seals fail between the upper and lower compartments and air from the upper compartment floods the lower, thus causing the leaking sodium to burn. It is assumed the loss of reactor coolant results in fission product release.
>
> "Three separate phases of the accident are examined: (1) sodium burning phase, (2) fission product heating phase, and (3) cooling phase."

As indicated in the quotation and in the subsequent discussion of Amorosi and Yevick, the question of what happens to the liner in the event of a major sodium leak was not addressed.

HNPF Cell Liners

Although the Hallam Nuclear Power Facility[69] (HNPF) was not a fast spectrum reactor, high-temperature (945°F) sodium was used as the coolant in this 256-MW(t) development reactor. This reactor, also known as the Sodium Graphite Reactor (SGR), was built and operated in the early 1960's; it is now decommissioned.

The reactor and auxiliary systems were housed in a confinement building (as opposed to a containment building) with the reactor and associated radioactive components located in steel-lined concrete-shielded cells below the operating floor level. The 1/2-in.-thick carbon steel (ASTM A-212) lining was welded to steel embedments in the structural (and shielding) concrete support. (Further details were not reported.[69]) Joints in the liners were welded in conformance with requirements of Section VIII of the ASME Boiler and Pressure Vessel Code using a minimum of two weld passes. The welds were visually inspected and leak tested during the erection stage using a vacuum-box and soap-bubble solution. Pertinent design and test requirements are given in Table 1.

According to the information presented, the lining was designed to prevent inleakage of water from the concrete backup into the cells and to maintain an inert-gas atmosphere within the cells as a precautionary measure against fire hazards. Pressure buildup of water vapor back of the steel liner, due to heat generation in the concrete, would be relieved to a recess around the periphery of the cells near the top. There appears to be no mention or concern about failure of the liner, due to excessive thermal strain, under sodium spill conditions. Consideration of this accident was apparently limited to pressure and temperature increases, as indicated by the following quotation from the Final Summary Safeguards Report:[69]

> "Considering the sodium contained both in the upper plenum of the reactor and in one primary loop, the maximum sodium spillage that could occur as a result of a primary loop rupture is 160,000 lb. Even though it is difficult to postulate a means whereby this amount of sodium could be released in the pipe tunnel or IHX cell, the consequences of an instantaneous spill of this magnitude have nevertheless been analyzed.
>
> "If 160,000 lb of sodium at 945°F (normal reactor outlet temperature) is instantaneously spilled from the primary sodium system

Table 1. Summary of criteria for HNPF primary system enclosure[69]

Criteria	Reactor cavity	Primary pipe tunnel—moderator coolant pump cell	IHX cell	Primary service cells			
				Fill tank vault	Hot trap[a]	Cold trap[a]	Service pumps[a]
Gross volume, ft^3	15,000	53,200	28,600	30,300	3,300	2,800	13,200
Operating pressure, in. H_2O	2–6	2–6	2–6	2–6	2–6	2–6	2–6
Design pressure, psig	2	2	2	2	2	2	2
Maximum pressure that can safely be contained within structural working stresses, psig	30	6	6	6	6	6	6
Construction test pressure (pneumatic) for gross leak and design strength check, psig	2 1/2	2 1/2	2 1/2	2 1/2	2 1/2	2 1/2	2 1/2
Test gas	He	N_2	N_2	N_2	N_2	N_2	N_2
Design criteria leak rate	1.37 ft^3/day at 6 in. H_2O at 220°F	3/4 of 1% std. vol/24 hr at 2 1/2 psig					
Basis of design leak rate	R/A tolerance level in bldg. with 45 $\mu Ci/cm^3$ in cavity	This measured leakage corresponds to less than 1/4 of std. leakage volume/24 hr at 6 in. H_2O maximum operating pressure to keep plant N_2 losses below 15,000 scf/month during operation					

[a]These cells tested together.

into an IHX cell, and if the nitrogen cooling system continues at the rated nitrogen flow, the nitrogen temperature in the cell would rise to a mean temperature of 242°F, which corresponds to a pressure rise of 2.8 psi. For the same conditions in the pipe tunnel, the mean nitrogen temperature would rise to 285°F, corresponding to a pressure rise of 3.85 psi.

"The pressures and temperatures resulting from these situations would only be attained if the vent valves fail to relieve the pressure, and are within the 6-psig working limits of the confinement structure for the cells and tunnels."

SNR-300 Cell Liners

The SNR-300 reactor,[70] under construction in the Federal Republic of Germany under the sponsorship of Germany, Belgium, and the Netherlands, is a 730-MW(t) LMFBR prototype that is scheduled[71] for criticality in the period 1978–1979. The containment concept selected for the 300-MW(e) plant is reported[72] to be suitable for similar plants with ratings in the range 1000 to 2000 MW(e).

Containment philosophy of this reactor plant is based[72] on the use of inner and outer zones of containment. The outer zone, functionally similar to containment buildings, is a rectangular concrete structure faced on the outside with a leak-tight steel structure separated a finite distance from the concrete. The space between the steel and concrete serves as a plenum and recirculating system. The building houses all radioactive materials and systems. Inside the rectangular containment building, a system of steel-lined cells, constituting the inner containment, contains the reactor, the primary heat transport systems, and a pressure-relief cell as indicated in Fig. 11. The steel liners are fastened to the concrete backup structure (additional details were not reported[72]) to provide a leak-tight membrane for containing an inert atmosphere (nitrogen) during normal operation and "... to protect the concrete against sodium sprays." The design-basis accident assumes the primary system is open to the inner containment. A dynamic model for analyzing the progress of an accident is discussed,[72] as well as some results; the behavior of the steel liner under this accident was not mentioned.

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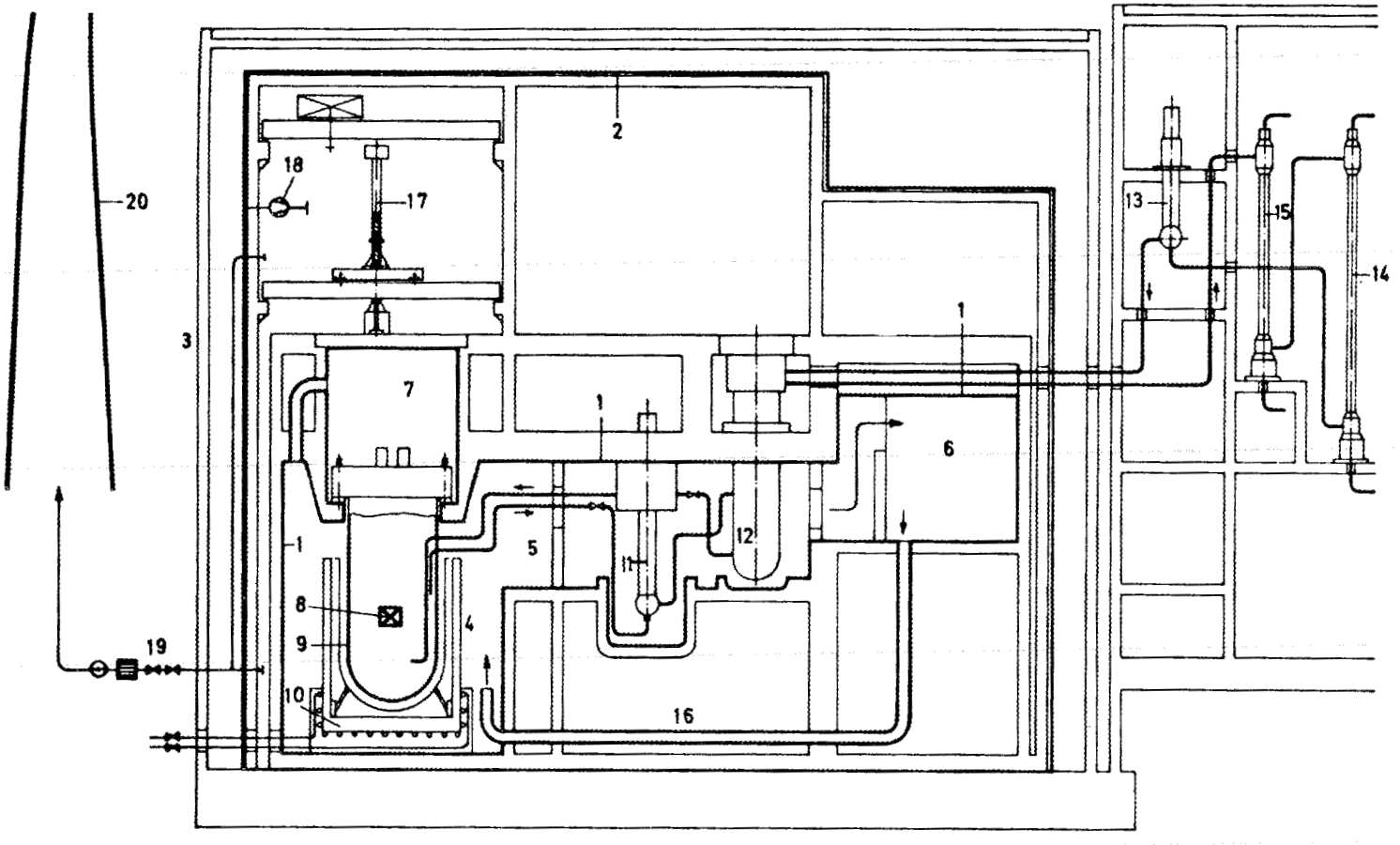

1 INNER CONTAINMENT
2 OUTER CONTAINMENT
3 REACTOR BUILDING
4 REACTOR CELL
5 PRIMARY CELLS
6 PRESSURE RELIEF ROOM
7 REACTOR PLUG CELL
8 REACTOR
9 REACTOR TANK
10 CORE CATCHER
11 PRIMARY PUMPS
12 IHX
13 SECONDARY PUMP
14 EVAPORATOR
15 SUPERHEATER
16 GAS CONVECTION CHANNEL
17 FUEL HANDLING MACHINE
18 REVENTING SYSTEM
19 CONTAINMENT AIR SUPPLY
20 STACK

Fig. 11. SNR-300 reactor building arrangement.

DISCUSSION OF LMFBR CELL LINER TECHNOLOGY

Practically all liquid-metal-cooled reactors built to date have included steel-lined concrete equipment cells as part of the structural design. The earlier "loop-type" concepts ("pot-type" concepts are not of interest for the purpose of this report) emphasized the liner as an aid in maintaining an inert-gas atmosphere in the cells during normal operation and as a barrier against leakage of radioactivity under accident conditions. Design criteria included pressures and temperatures expected from sodium reactions with the oxygen content of the cell. More recently, LMFBR designs have expanded the functional requirements to include the liner as a barrier to prevent hot sodium from coming into contact with the concrete structure. In particular, the designers of SEFOR and FFTF assessed the performance of the cell liners under assumed massive spills of coolant from the primary components and systems; secondary (i.e., nonradioactive sodium) systems appear to have been excluded from consideration. Guard vessels have generally been provided for protection against spills from components; double-walled piping has been used in some instances. As would be expected, LMFBR cell liner technology has not yet reached the level of maturity evident in containment technology for water- and gas-cooled reactors, even though the concepts and construction details are largely derived from these sources.

In arriving at a final design of a cell liner, one has to progress as a minimum through the following sequence of events:

1. establish design criteria, including pressure, temperature, and leakage requirements;
2. produce conceptual design, based on system layout and functional requirements;
3. analyze liner design for all loading conditions;
4. assess performance of liner design in light of established acceptance criteria.

The first, third, and fourth of these are the most bothersome.

In establishing the design criteria, consideration should be given[73–76] to the fact that sodium fires have a much higher energy release to the cell

atmosphere than nominal sodium leaks; exothermic reactions are possible between sodium and some insulation materials, and liquid sodium will react violently with the water normally contained in concrete. Sodium pool fires are amenable to analysis[54] and are highly dependent on geometry, cell volume, burning surface area, and heat transfer surface area.[77] On the other hand, sodium spray fire analyses are less exact, although upper theoretical and experimental limits have been shown to be predictable.[77] The oxygen level and sodium temperature, particle size, and quantity have a significant effect on the pressure rise.[78]

Structural analyses of cell liners present difficulties, with the greatest of these being related to regions of discontinuities (e.g., penetrations and wall-to-wall, wall-to-floor, and wall-to-wall-to-floor junctions). Yet it is in these locations that the highest stresses will be concentrated and where failure is likely to initiate. Almost invariable, elastic-plastic analyses, using two- or three-dimensional models, are necessary to evaluate the stresses and strains in these regions. As pointed out by Townley,[1] until recently little was known about the factors that affect the high-temperature performance of complex structures. Design has been largely dictated by experience and by the knowledge that certain components gave satisfactory service. He notes that such experience, by its nature, cannot be extrapolated with certainty to structures differing in size or materials or subjected to operation in a different regime.

The cell liner design used in the SEFOR plant differed greatly from that used for the hot liners in the FFTF structure (SEFOR had the liner rigidly attached to the backup concrete structure, whereas the FFTF has a "free-floating" liner), even though both concepts were designed to accommodate massive sodium spills. In assessing design performance, the designers of these facilities concluded from analyses that the liners would maintain leak-tightness for the assumed accident conditions. Since experimental work in support of design or as proof of concept was not conducted in either case, justification for the conclusion is not readily apparent.

In our discussions with individuals having knowledge of sodium technology and in our limited literature review, we found no reference to

significant sodium spill accidents in steel-lined cells. However, one incident[79] involving the performance of a LWR containment building liner is pertinent to this survey. In the incident, which occurred at the Indian Point unit 2 plant in November 1973, an 18-in. feedwater line failed with a fracture adjacent to a fillet weld between the feedwater line and the end plate that is welded into the penetration sleeve. The fracture extended approximately 180° around the pipe. Impingement of steam and water on the liner in the vicinity of the line break caused the liner to bulge inward over a large area.

The liner, constructed of 3/8-in.-thick ASTM A-442 welded steel plates, is anchored to the 4.5-ft-thick concrete structure with 1/2-in.-diam by 7-in.-long studs on a 14-in. vertical pitch by 24-in. horizontal pitch. The studs have a 2-in.-long 90° bend at the embedded end for additional pull-out strength. Through a construction error (found after the incident), two alternate rows of the studs were omitted in the vicinity of the damaged area, resulting in a 28-in. vertical spacing for the affected panels.

After the incident, measurements showed that the liner had bulged inward over an area covering a bandwidth of 2.5 to 3.0 ft by ∿50 ft in the circumferential direction. The most highly strained (∿1.33%) area occurred where the bulge inward was about 1.25 in. The bulged area was more or less centered (elevation wise) about the rows of missing studs. Nine studs in the row between the two missing rows were determined to be broken. Subsequent inspection and tests showed no cracks or leaks in the liner, and the liner was judged acceptable for further operation.

This incident, while less severe than a massive sodium spill, does enhance confidence in the ability of a stud-anchored liner to deform measurably without violating its containment integrity. Also, it tends to support the contention[34] of some designers that stud-anchored liners can be designed to accommodate massive sodium spills.

LMFBR CELL LINER DESIGN

Cell liner design practices used in the past for liquid-metal-cooled reactors evolved largely from water-cooled-reactor containment experience. In fact, with the exception of the hot liner concept used in the FFTF, there are few distinguishable differences. Consideration of the consequences of a massive sodium spill, however, does introduce significant differences, at least in the area of design evaluation.

Specific design criteria for concrete reactor and containment liners have been formulated only recently.[18] Prior to this time, design and construction of steel liners, formally or informally, followed the applicable rules of Sections III and VIII of the ASME Boiler and Pressure Vessel Code. General design practices developed during this period were summarized by Tan.[7] More specific criteria and philosophy were discussed in detail by Halligan.[80] The newly formulated criteria[18] were discussed by Lee and Gurbuz,[10] primarily with regard to liner design for PCRV applications in gas-cooled reactor technology. Although the new containment liner criteria are specifically for nuclear power plant containment structures (as opposed to reactor vessels) having a design pressure in excess of 5 psi, the design concepts are generally applicable to LMFBR equipment cell liners. Some of the unique problems associated with liquid-metal systems, as reflected in the following functional requirements, require special consideration and may necessitate modification and/or additional criteria.

Basically, it is generally accepted that LMFBR cell liners should be designed to

1. provide a leak-tight (or low inleakage) containment for the inert-gas atmosphere during normal operation,
2. prevent (or minimize) release of fission products to the containment building under accident conditions,
3. prevent contact between the sodium coolant and the concrete structure in the event of accidental sodium spills,
4. facilitate cleanup operations following an accidental sodium spill.

Current design practices for cell liners are discussed below.

Liner Plates

To satisfy the above functional requirements, the liner must be designed to resist all direct loads and to accommodate imposed deformations without loss of containment integrity (leak-tightness). Although the liner is usually constrained to follow the concrete backup structure (this is required in the proposed code[18]), liner strength is not normally considered in assessing the adequacy of the concrete structure. However, due to the constraint, interaction between the concrete and the liner must be considered in determining liner behavior. Normally this involves such loads as concrete creep and shrinkage, prestressing (where applicable), accident pressures, normal and accident thermal expansions, normal and abnormal dead loads, mechanical loads (such as reactions at points of support or penetrations), and earthquakes.

Lee and Gurbuz[10] recommend consideration of the following categories of loading combinations (as defined in the new code[18]) in determining the liner design strains:

1. construction category,
2. normal category,
3. abnormal category,
4. extreme environmental category.

The severe environmental category is not included because the additional loads introduced in this category do not affect the liner design strains appreciably. Noticeably, the failure category specified by the proposed code for steel-lined concrete reactor vessels is not believed applicable to liner design.[10] In fact, limits on liner component stresses and displacements under failure conditions are not imposed. Since some of the examples considered for inclusion in this category by the proposed code are not too unlike conditions that might be hypothesized for LMFBR cell liners, this exclusion may warrant further evaluation.

Current design practice assumes that the anchor spacing and plate thickness are chosen such that the plate does not experience elastic buckling. Local inward deflection or local plastic buckling may be permitted if it can be shown that rupture does not occur. Since the loads producing inward

displacements of the liner are generally relieved by the displacement or local buckling, the displacement and material strains are self-limiting. Local buckling is acceptable if the local strains do not exceed allowable ductility limits or produce fatigue cracks in cases of cyclic loading. Limited studies have been conducted to establish the conditions for buckling and postbuckling behavior of specific liner plate—anchor system designs.[21,23–25,41] Lee and Gurbuz[10] summarized pertinent design experience with regard to buckling. The approach generally taken has been to conduct sufficient tests and analyses to justify particular design parameters and loading conditions. (This is primarily apropos to water- and gas-cooled reactor containment technology.) Due to the uncertainties in local buckling behavior, only small variations in these experimentally based parameters are permitted. It is usually considered necessary to perform additional testing and analysis if significant changes in design parameters and/or loading conditions are encountered.

The stresses, strains, and displacements in the liner plates can be analyzed by one of the methods discussed earlier. The computed values must not exceed the acceptance criteria established in the proposed code.[18] Testing may be necessary to establish the precise value of a particular criterion, since many of the allowable parameters are based on ultimate material characteristics. Lee and Gurbuz[10] provide a good discussion on the assessment of the allowable stress and strain values.

The concrete temperature is of particular interest in evaluating the performance of cell liners under sodium spill conditions. The proposed code[18] specifies the following limits on this parameter in concrete containment structures (see paragraph CC-3430 of Ref. 18):

> "a. The following temperature limitations are for normal operation or any other long-term period. The temperatures shall not exceed 150°F, except for local areas which are allowed to have increased temperatures not to exceed 200°F.
>
> "b. The following temperature limitations are for accident or any other short-term period. The temperatures shall not exceed 350°F for the interior surface. However, local areas are allowed to reach 650°F from steam and/or water jets in the event of a pipe failure.
>
> "c. Higher temperatures than given in Items (a) and (b) may be allowed in the concrete if tests are provided to

> evaluate the reduction in strength and this reduction is applied to the design allowables. Also evidence shall be provided which verifies that the increased temperatures do not cause deterioration of the concrete either with or without load."

The limits in item b appear to be less restrictive than those previously used in LMFBR plants, although one might question what is a "short-term period."

Liner plate materials must not be susceptible to brittle failure and must possess sufficient ductility to accommodate the imposed loads and deformation without rupture. Similarly, in regions subject to intense neutron irradiation, consideration should be given to the deleterious effects of nuclear radiation on liner plate mechanical properties.

Anchors

The proposed code specifies that ".... The liner shall be anchored to the concrete containment. This does not preclude local flexural deformation between anchor points." With the exception of the FFTF hot liner concept, liquid-metal system cells have followed this practice. This is an area where modification in scope and/or additional criteria may be necessary to apply the proposed code to future LMFBR designs.

The anchors may be either continuous structural sections, such as tees, angles, channels, bars, etc., or combinations of these shapes, or studded anchors such as Nelson studs or L-shaped anchor studs. The size and spacing of the anchors are chosen to control the response of the liner plate in a predictable manner for all loads and load combinations. The anchors must be designed to withstand forces in the plane of the liner, forces normal to the liner, and moments imposed by the liner plate or penetrations. The anchor design and analysis should consider at least the following factors:

1. unbalanced loads on the anchor resulting from initial outward curvature of the liner on one side of the anchor and inward curvature of the liner on the other side of the anchor,
2. unbalanced loads on the anchors resulting from possible failure of adjacent anchors,
3. variations in liner plate thickness,

4. variations in material properties (yield strength, Poisson's ratio, modulus of elasticity) of the liner plate material,
5. structural discontinuities at liner plate seams,
6. variation in anchor spacing,
7. variation in anchor stiffness,
8. local concrete crushing in the anchor zone.

The anchor loads may be determined either by assuming the liner plate remains elastic under all loading conditions or by performing an elastic-plastic analysis. If the latter method is used, biaxial compressive yield test data are required for the liner plate material.

The design basis for selecting the anchor size and spacing must preclude progressive failure in the event of a defective or missing anchor. Massive deformation of the liner plate must be prevented. These design requirements have resulted in the liner being anchored at relatively close intervals, typically 12 to 18 in. Closer spacings (6 to 8 in.) have also been used.

Design limits are specified in the proposed code[18] for anchor mechanical loads and displacement-limited loads. Mechanical loads are those in which structural deformation does not lead to relaxation of the condition causing the load. Examples of such loads are external pressure on the liner, equipment attachments (brackets), and, possibly, penetrations. Displacement-limited loads are self-limiting or self-relieving in nature. According to Lee and Gurbuz,[10] most anchor loads are in the latter category.

Another important design problem concerns the interaction of tensile and shear forces on the anchor. It appears that little attention has been given to this facet in previous designs. Also, the proposed code apparently does not address the problem. This is an area in need of criteria for guidance. Lee and Gurbuz[10] suggest, in the absence of data, that an elliptic interaction relationship be used. They cite the analogy of tension-shear allowables for bearing-type bolts being based on such a curve. Since the anchors are welded to the liner plate and since welding tends to be a troublesome area with respect to quality control, the importance of this biaxial stress condition should not be overlooked.

Penetrations

The number of penetrations through containment liners should be minimized. The penetrations that are required should be located, whenever possible, in regions of low liner loading. Penetrations should be designed with shear anchors to transmit loads from the penetration to the structural concrete. In addition to static loads, the penetration assembly should be capable of accommodating dynamic loads generated by pipe rupture. The liner plate thickness may be increased near penetrations to reduce stress concentrations. Bellows connections have been used for penetrations where large lateral movement of the connecting pipe is required.

Penetration assemblies are analyzed by the applicable methods of Section III, Division 1, of the ASME Boiler and Pressure Vessel Code. The analysis must consider the effect of concrete confinement for penetrations embedded in the concrete structure.

Special Design Problems with Sodium Systems

The overall objectives of sodium cell liners are essentially the same as containment liners for other reactor coolant systems. However, there are several characteristics of sodium systems that necessitate special design considerations. Some of the major considerations are discussed below.

The possibility, and consequences, of sodium fires in the event of an accidental spill requires special design considerations. Most sodium system cells have been designed to operate with nitrogen atmospheres to prevent or minimize this problem. In this case, inleakage of air is a design parameter as well as outleakage of cell gas. The reaction of sodium with oxygen contained in the inert atmosphere (generally 1 to 5%) may be a significant source of heat and should be considered in the thermal analysis of accident conditions involving sodium spills.[54,58–60]

The energy released by other chemical reactions involving sodium is also of concern in cell liner design.[74–78] The possibility of sodium reaction with water requires that the cell interior be dry. Further, the concrete (and, possibly, thermal insulating materials) must be protected from exposure to hot sodium in the event of spills. This consideration provides additional incentive for design criteria that preclude liner failure.

The thermal effects of sodium spills influence cell liner design from two aspects. First, the increase in temperatures may cause significant liner distortion and large thermal expansion loads. Second, the higher temperatures may have an adverse effect on the physical or mechanical properties of the structural materials. The extent of the problem created by thermal expansion is not well defined at the present. As described earlier, the design of Hallam Nuclear Power Facility and SEFOR used liners anchored firmly to the concrete. The design of SEFOR was based on a large sodium spill with distortion and buckling of the liner plate but without liner rupture. The design of the FFTF used a different philosophy for those liners or portions of liners that would experience temperatures above 205°F in the event of sodium spills. The FFTF hot liner design consists of a floating liner concept to accommodate thermal expansion. Vertical and radial clearances are provided near the floor-to-vertical-wall corners to provide relief for thermal expansion. Expansion joints in the vertical walls are used to provide additional relief for thermal expansion. Since the cost of the floating liner may be a factor of 10 times the cost of anchored liners, there is considerable economic incentive to use anchored liners whenever possible.

The adverse effect of the elevated temperatures on the properties of concrete can be eliminated or minimized by using insulation and heat-removal systems. A combination of firebrick and insulating brick was used between the liner and the structural concrete in the FFTF. For gas-cooled reactor designs, cooling coils between the liner and concrete and insulation on the inside of the liner have been used to control both liner and concrete temperatures. This approach and the Austrian hot liner concept[81] may be attractive alternatives to floating liners for solving thermal expansion problems.

The cell liner design must consider missiles generated by explosive conditions that may be developed in the sodium system. The design of EBR-II used a multiwall liner of steel and concrete as a blast shield. More recent designs, including that of the FFTF, have used guard vessels around the sodium system components. Although the primary purpose of the guard vessels is to maintain the coolant system, they also provide some protection against missiles for the cell liner.

Fabrication and Testing

Two approaches have been used for installing anchored cell liners. In one method, the anchors are embedded in the concrete, and the liner plate is attached to these anchors, by welding, after the concrete casting forms are removed. In the second method, the liner is used as a form for the concrete, with the anchors being attached to the plate prior to installation. Temporary support must be provided for the liner in the second method to prevent excessive displacement or bulging during the concrete casting operation.

Rules for cutting, forming, and bending are given in the proposed code.[18] These rules include requirements for qualification of forming and bending processes, forming tolerances, and maximum-allowable defects in final welded joints.

The welding of the liner plates and attachments to the liners must conform to the requirements of Section IX of the ASME Boiler and Pressure Vessel Code. Additional welding requirements are given in Ref. 18. All liner butt welds are required to be radiographed if they are accessible for such inspection. All pressure-containing welds are required to be examined by the vacuum-box bubble-solution test or the gas-medium test where the welds are accessible. Where radiography and vacuum-box examinations are not possible because of inaccessibility or weld joint design, magnetic-particle or liquid-penetrant examination may be used.

Structural integrity and leak-tightness of the cells must be demonstrated. Tests may be performed to correlate measured structural response with theoretical predictions. Strain measurements are needed unless deflections can be clearly correlated with strain. Integrated leakage tests are required initially and during the service life to establish leak-tightness.

IDENTIFICATION OF RESEARCH AND DEVELOPMENT NEEDS

In the past, the practice has been to rely on analysis to infer the adequacy of cell liners to maintain their leak-tightness under postulated accident conditions. This practice will likely continue in the future, since tests on the completed structure under simulated accident conditions appear to be a most unattractive alternative. Similarly, proof-of-concept tests on prototypical models may entail an undue economic burden. Thus, the lack of a viable alternative to analysis places a heavy responsibility on the designer to specify credible design criteria, to analyze the design with reliable analytical models of demonstrated validity, and to assess the possible failure modes by comparison with generalized theoretically and/or experimentally established failure criteria. Based on the information reviewed in the preparation of this report, the evidence in support of the contention that these actions are satisfactorily accounted for in the current state of the art, when viewed in its entirely, is not totally convincing. This is not intended as criticism toward any reactor plant or designer; it is intended to reflect our appraisal of the degree of maturity attained thus far in LMFBR cell liner technology. There are examples of disciplined analysis, and there are examples, in our opinion, of unjustified or unsubstantiated claims.

It is our opinion that further research and development are needed to permit a valid assessment of LMFBR cell liners under all design conditions. It is believed that confidence in liner performance can be materially increased if research and development in the directions suggested are pursued aggressively. The need is greater in some areas than in others, but beneficial results can be obtained in all the suggested areas.

The two most recent LMFBR cell liner designs are radically different in concept (i.e., fixed vs floating liner), yet both are claimed to accommodate massive sodium spills without loss of containment integrity. Since the cost of the floating liner concept (the newer design) greatly exceeds that of the fixed liner, a thorough design study should be initiated to evaluate in detail the two concepts for a common set of assumed conditions.

Benefits from such a study would include:

1. an assessment of the analytical models used to analyze the concrete structure and the steel liner, particularly in the regions of two- and three-dimensional discontinuities;
2. a detailed analysis, using two- and three-dimensional nonlinear programs as required, of the critical corner junctions to determine stresses, strains, and displacements in the liner;
3. an analysis of the liner-anchor combination (in the fixed liner concept) under conditions of gross distortion;
4. a clear and definitive statement of the failure criteria used to judge the designs;
5. an exposition of the relative complexity (indicative of cost) in each design concept;
6. revelation of the gaps in technology at each step of the procedure;
7. the basis for an integrated program for resolving the uncertainties in the design.

Initiation of a design study such as outlined above would appear to warrant high priority.

Another area of research and development believed to be of high importance involves experimental testing of prototype steel-lined cells subjected to sodium spills. The initial tests should concentrate on general behavior of the liner to massive sodium spills in the absence of fires to define specific problem areas and general failure patterns. This type of information is needed to provide direction to analytical studies and to subsequent tests. Follow-on testing should be directed toward accumulation of basic design data needed as input to the analytical models. In planning the test program, consideration should be given to the response of the cell liner to sodium sprays and jets and to sodium spills involving chemical reactions. A final proof-of-concept test series is needed to validate analytical models used in the design procedure and to demonstrate the ability of the liner to remain leak-tight during and after a massive sodium spill.

Another area in need of research is rupture data under multiaxial stress states. In the critical regions of a cell liner (e.g., corners and

penetrations), the surfaces of the liner are usually in a biaxial, compressive stress condition, while significant triaxial stress patterns may exist through the thickness. Most of the rupture data used to assess failure were obtained from uniaxial specimens loaded in tension, and it is often necessary to predict rupture under multiaxial stresses from these data. It would appear that basic research is needed to provide rupture data on liner materials under, as a minimum, compressive biaxial loading conditions. Of particular interest is short-term, high-strain-rate data, since these conditions are expected for cell liners under sodium spill conditions.

A somewhat related problem exists for welded construction. It is generally assumed that the liner system behaves as if constructed throughout of material having uniform properties. However, it is well known that welds introduce regions where the stress to rupture and the ductility at rupture are considerably different from the parent plate. Evidence cited by Townley[1] suggests that the rupture life of a weldment will always be less than that of the parent material unless the deformation rates of the weld metal and the parent metal are closely matched. Since numerous weld joints are involved in the construction of a cell liner, it would appear that research is needed to resolve this uncertainty.

Bergstrom et al.[17] pointed out that design of a massive concrete structure to accommodate significant temperature gradients that might arise during an accident often dictates the structural requirements. There appear to be inadequate design data and failure criteria available to the designer for predicting the performance of thermally loaded structures with certainty. While this is not a liner problem per se, the performance of the liner is intimately related to that of the concrete backup structure. Thus, it is suggested that research and development related to design of thermally loaded massive concrete structures would be beneficial.

Similarly, the properties and performance of concrete, both structural and shielding types, are inadequately known for the range of temperatures and times expected under sodium spill conditions. It was suggested[34] that research and development be initiated to provide more definitive information on (1) the physical properties of concrete (both structural and shielding) as a function of temperature, (2) allowable short-term strength of concrete

as a function of temperature, (3) the mechanisms and effects of temperature on concrete degradation, and (4) methods for modeling heat transport in heavily reinforced concrete.

Although this report is primarily concerned with cell liners, it is perhaps appropriate to mention the need expressed[34] for research related to sodium reactions. In particular, it is known that high-temperature sodium in contact with concrete produces a rather violent exothermic reaction.[58] It appears that the reaction has both mass and temperature thresholds below which the reaction is not self-sustaining. Further research appears in order to define the limits and to permit modeling the kinetics so that cell liner design criteria can be more realistically established.

Modeling of sodium pool burning in the FFTF was accomplished with the SØFIRE-II and CACECØ programs.[54] These are one-dimensional codes and are cumbersome, inefficient (in computer usage), and require large memories to run. A need was expressed[34] to modify the codes to (1) improve computer efficiency, (2) include slender, two-dimensional cylindrical geometry to permit better modeling of cells, and (3) include provisions for cell-to-cell transport of gases through interconnecting piping tunnels and open penetrations during accident conditions.

With the exception of the hot liners in the FFTF, cell liner concepts for LMFBRs have advanced very little from those used in the first plants constructed. Although analytical techniques and construction details related to anchoring the liner to the concrete have evolved considerably, innovative concepts have not appeared in practice. It is suggested that design studies be undertaken to evaluate new concepts to determine feasibility and/or practicality of promising ideas. Some ideas that may warrant investigation include (1) the use of a zone of high-temperature, insulating concrete (sacrificial possibly) between the liner and the structural concrete; (2) the use of fiber (chopped-wire) reinforced concrete[82] to give higher strength, better matching of thermal expansion, and improved heat transport characteristics in the region adjacent to the liner; (3) the PCRV hot liner concept under development in Austria;[81] and (4) the use of liners anchored with studs designed to fail (under sodium spill conditions) without rupture of the liner plate.

It is apparent that containment structure liner criteria established in the proposed code[18] are not altogether compatible with current concepts and practices for LMFBR cell liners. An assessment of the proposed criteria with regard to LMFBR cell liner applications is needed to identify areas of conflict, inadequate guidelines, and lack of acceptance criteria. The results of such a study would identify areas of research and development necessary to provide the additional data and would serve as the basis for initiating revision and/or modification of the proposed code.[18]

The above discussed needs suggest that an integrated research and development program can, if successfully concluded, resolve the uncertainties and provide the basis for increased confidence in the ability of LMFBR cell liners to perform as designed. Such a program might be logically structured as follows.

Task 1 — Program Planning and Analysis

This task would provide for planning, management, direction, analysis, and coordination of the various activities under investigation. Reporting, scheduling, scope of investigation, and other managerial functions also would be assigned to this task.

Task 2 — Cell Liner Design Studies

This task would study and evaluate in detail existing and new liner design concepts. It is believed that problem areas, deficiencies in analytical models, lack of input design data, failure criteria, heat transfer difficulties, etc., will become more readily apparent and subject to better definition through realistic design studies. Results of these studies would provide input and guidance to the other task areas.

Task 3 — Evaluation of Concretes and Concrete Structures

Since the behavior of the steel liner is intimately related to the massive concrete structure, liner analysis must include the influence of the structure. This task would investigate these aspects as well as properties and performance of concrete under short-term high-temperature

conditions. Special concrete types, such as shielding, high-temperature insulating, and fiber reinforced, would be included as needed. Both experimental and analytical investigations are envisioned for this task.

Task 4 — Evaluation of Analytical Models

A number of models and computer programs are currently used by architect-engineers to design cell and containment vessel liners. This task would evaluate selected models in view of the test results obtained under Task 5. Similarly, modifications and/or development of new models to improve the ability to predict the behavior of cell liners under postulated accident conditions would be included.

Task 5 — Experimental Model Testing

Direction and evaluation of the analytical studies, of necessity, depend heavily on the results of an experimental test program. Initially, relatively simple spill tests should be performed on instrumented models that simulate floor conditions in a lined cell to obtain an indication of the severity of the problem and the types of failure likely to occur. Subsequently, tests should be conducted to obtain basic design data needed as input to the analytical models. Finally, it may be desirable (or necessary) to test small modeled cells so that data can be obtained for evaluating and validating the analytical models used in the design. Such a test would also serve as a proof of concept to demonstrate the ability of the liner to remain leak-tight under simulated accident conditions. The test program would be expected to include tests with sodium sprays, jets, and massive spills with and without chemical reactions.

Task 6 — Metallurgical Studies

This task would be devoted to basic studies related to fracture mechanics and failure criteria of liner plate materials (welded and unwelded) under multiaxial, compressive stress conditions.

Task 7 — Chemical Reactions and Modeling

This task would provide basic reaction kinetics data as needed (to supplement existing programs) to permit realistic definition of design criteria. Modification and/or improvement of existing models and programs would be included.

Task 8 — Application of Proposed Code to LMFBR Cell Liners

This task would assess the applicability of the proposed structural design code to LMFBR cell liner design. Areas of conflict, lack of or inadequacy of guidelines, and acceptance criteria would be identified. The results would be used to initiate research and development needed to provide a rational and acceptable set of code criteria and to initiate revision and/or modification of the code to make it compatible with current LMFBR cell liner design concepts and practices.

The indicated tasks present a topical outline of how a research and development program might be logically formulated. Obviously, the details and scope of such a program require far more definition than has been given in this brief discussion.

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